GAMES AND ECONOMIC BEHAVIOR **17,** 147–176 (1996)
ARTICLE NO. 0100

Moral Hazard and Adverse Selection in Procurement Contracting*

James C. Cox and R. Mark Isaac

Department of Economics, University of Arizona, Tucson, Arizona 85721-0108

Paula-Ann Cech

Department of Economics, DePaul University, Chicago, Illinois 60604

and

David Conn

Department of Economics, University of Arizona, Tucson, Arizona 85721-0108

Received May 20, 1994

A model of procurement contracting is developed and tested in laboratory experiments. Market performance results are presented for both fixed-price and cost-sharing contracts. Contracts are awarded with first-price sealed-bid or second-price sealed-bid auctions. The environment contains post-auction cost uncertainty and opportunity for unmonitored effort in contract cost reduction. Cost-sharing contracts are found to reduce procurement expense but also to be inefficient because of their induced moral hazard waste and cost overruns. *Journal of Economic Literature* Classification Numbers: C72, C92, D44, D61, D82, H57, L14.

1. INTRODUCTION

Government contracts for purchasing major weapons systems and for building roads, bridges, airports, harbor facilities, and buildings are usually awarded by soliciting bids from qualified firms and then accepting the

* This manuscript is part of the GEB special issue devoted to Experimental Economics, Volume 10, No. 1, edited by J. O. Ledyard and T. R. Palfrey. The authors received financial support from the Rand Corporation, the Alfred P. Sloan Foundation, and the National Science Foundation (Grant SBR-9108888). Research support services were provided by the Economic Science Laboratory at the University of Arizona. The first author is grateful for the hospitality of the Tinbergen Institute and CREED at the University of Amsterdam. Sheryl Ball and Joseph Campbell assisted in conducting the experiments. Data from the experiments are available from the authors.

0899-8256/96 $18.00

lowest bid. The contracting environment is characterized by information asymmetries, leading to problems with adverse selection and moral hazard. Adverse selection occurs when the government accepts the bid of an inefficient producer because it cannot observe the bidders' expected production costs before awarding the contract. Moral hazard arises after the contract has been awarded because the government cannot observe all aspects of the firm's efforts to hold down production costs, and hence the enforceable terms of the contract may not provide sufficient incentive for the firm to adopt the efficient level of cost-reducing effort.

Government contracts typically have one of three alternative forms. Under a *fixed-price* contract, the government's payment is simply the bid price from the auction. With a *cost-plus* contract, the government's payment consists of the firm's observed production cost plus a fee that is fixed in advance or is a function of cost. Under a *cost-sharing* contract, the government's payment consists of the bid price plus (or minus) a prespecified proportion of cost overrun (or saving). The cost overrun (or saving) is usually calculated as the difference between observed production cost and the bid price of the contract. Fixed-price, cost-sharing, and cost-plus contracts are all members of the class of *linear* contracts.

In our experiments, eight treatments are constructed by intersecting each of four contract designs with both post-auction cost certainty and cost uncertainty. Of the four contract designs, two are fixed-price contracts and two are cost-sharing contracts. For the fixed-price contracts, we used both a first-price sealed-bid (F.P.) auction and a second-price sealed-bid (S.P.) auction. In the first-price auction of a fixed-price contract, the low bidder wins the contract and is paid the amount of his bid. In the second-price auction, the low bidder is awarded the fixed-price contract and is paid the amount of the second-lowest bid. The cost-sharing contracts are both awarded with first-price auctions. Thus, payment in a cost-sharing contract is the sum of the low bid and a ‘‘payment adjustment.’’ This adjustment is a percentage of cost overrun or underrun (observed cost minus the low bid). The two cost-sharing contracts use reimbursal rates of either 30 or 85%.

The market data used in empirical analysis include winning bids, budgetary procurement expense, and several measures of production cost and efficiency. Two aspects of our empirical results are especially noteworthy. First, the central theoretical predictions from the model developed in Section 2 are generally supported by the data. Second, the data reveal a generally *inverse* relation between budgetary efficacy and other welfare and efficiency measures: the lower the budgetary procurement cost is, the worse the inefficiency associated with moral hazard.

2. THEORY AND HYPOTHESES

The model that we test is similar to models previously developed by Holt (1979a, 1979b, 1980) and McAfee and McMillan (1986). We use McAfee and McMillan's specification of contracts and the contracting environment. There is a fixed number, n, of potential contractors, each of whom bids on a contract. If granted the contract, agent i's observable cost of fulfilling it is c_i. Assume that c_i consists of three distinct components,

$$c_i = c_i^* + w_i - \xi_i, \tag{1}$$

where c_i^* is the certain base cost, w_i is a random variable that represents uncertain components of cost, and ξ_i is the discretionary cost reduction. This discretionary cost reduction by agent i comes at the expense of an effort cost, $h(\xi_i)$, that is not observable by the buyer. Assume that zero discretionary cost reduction has zero effort cost ($h(0) = 0$) and that effort cost increases ($h'(\cdot) > 0$) at an increasing rate ($h''(\cdot) > 0$). Since effort cost, $h(\cdot)$, is not observable by the buyer, it is not reimbursable under any feasible contract. Realizations of c_i^* and w_i, as well as the choice of ξ_i, are observable only by agent i (and the experimenters, in a controlled experiment). However, the realized total cost, c_i, is observable by everyone *after* procurement has occurred. Assume that the c_i^* are independently and identically distributed (i.i.d.) random variables with lowest and highest possible values of c_ℓ and c_h. Also assume that the w_i are i.i.d. with zero expected values.

Define b as the *bid price* of the contract. If the contract is awarded by a first-price sealed-bid auction then b is the amount of the lowest bid. If the contract is awarded by a second-price sealed-bid auction then b equals the second-lowest bid. If bidder i submits the lowest bid and is awarded the contract then the payment to i is

$$p_i = b + \alpha(c_i - b), \tag{2}$$

where the cost-sharing rate, α, is the proportion of cost overruns (or savings) that will be reimbursed by (or repaid to) the buyer. When $\alpha = 1$, the contract is *cost-plus* (with planned economic profit equal to zero). When $\alpha = 0$, the contract is *fixed-price*. When $0 < \alpha < 1$, it is a *cost-sharing* contract. Cost-plus contracts are generally dominated by other types; hence we will subsequently only consider contracts such that $0 \leqq \alpha < 1$.

If bidder i is awarded the contract then his profit, π_i, equals the difference between the contract payment, p_i, and the sum of the observable cost, c_i, and the non-observable effort cost, $h(\xi_i)$. Equations (1) and

(2) imply that contract profit is given by

$$\pi_i = p_i - c_i - h(\xi_i) = (1 - \alpha)(b - c_i) - h(\xi_i). \tag{3}$$

The assumed sequence of events is as follows. At the time bids are submitted, each potential agent knows his own base cost c_i^*, the contract form (i.e., α), the type of auction (first-price or second-price), the probability distribution for others' base costs, and the probability distribution for everyone's uncertain cost. After bids are submitted and the low bidder is awarded the contract, the low bidder decides on the discretionary cost adjustment, ξ_i, and then learns the realization of the random component of cost, w_i.

McAfee and McMillan (1986, p. 328) derive an implication of expected utility maximization for the low bidder's choice of discretionary cost reduction as follows. Substitute (1) into (3) and then maximize π_i with respect to ξ_i. Assuming that $h'(0) < 1 - \alpha$, the first order condition for the profit-maximizing level of discretionary cost reduction (ξ_i^o) is

$$h'(\xi_i^o) = 1 - \alpha. \tag{4}$$

Since $h''(\cdot) > 0$, there exists an inverse, $g(\cdot)$, to the function, $h'(\cdot)$, that is strictly increasing. Therefore, the model predicts

$$\xi_i^o = g(1 - \alpha) \qquad \text{and} \qquad \frac{d\xi_i^o}{d\alpha} = -g'(1 - \alpha) < 0. \tag{5}$$

Statement (5) gives us the first testable implication of the model:

HYPOTHESIS 1. *Discretionary cost reduction equals $g(1 - \alpha)$ and it decreases as the cost-sharing rate, α, increases.*

In other words, the model predicts inefficiency—from moral hazard—for cost sharing ($\alpha > 0$) contracts and more inefficiency with higher sharing rates.

Additional testable implications can be derived by strengthening the assumptions of the model. We show in the Appendix that if all bidders are risk neutral and base costs are uniformly distributed on the interval $[c_\ell, c_h]$ then a Nash equilibrium bid and cost reduction function for the first-price auction is

$$b_i^N(c_i^*) = c_i^* + \frac{c_h - c_i^*}{n} + \frac{h(\xi^o)}{1 - \alpha} - \xi^o. \tag{6}$$

We also show in the Appendix that if base costs are uniformly distributed on $[c_\ell, c_h]$ and all bidders are risk neutral then the dominant strategy bid and cost reduction function for the second-price auction is

$$b_2^N(c_i^*) = c_i^* + \frac{h(\xi^o)}{1-\alpha} - \xi^o. \tag{7}$$

In addition, we show in the Appendix that (7) is the dominant strategy bid function for risk averse and risk-preferring (as well as risk neutral) bidders when there is no post-auction cost uncertainty.

We also show in the Appendix that if all bidders have constant absolute risk averse (CARA) preferences with coefficient λ, base costs are uniformly distributed on $[c_\ell, c_h]$, and post-auction (uncertain) costs are uniformly distributed on $[w_\ell, w_h]$, then a Nash equilibrium bid and cost reduction function for the first-price auction is

$$b_1^A(c_i^*) = c_i^* + \frac{h(\xi^o)}{1-\alpha} - \xi^o + \frac{1}{\lambda(1-\alpha)}(\ell n X - \ell n Y), \tag{8}$$

where

$$X = \frac{e^{\lambda(1-\alpha)w_h} - e^{\lambda(1-\alpha)w_\ell}}{\lambda(1-\alpha)(w_h - w_\ell)} \tag{9}$$

and

$$\begin{aligned} Y = {} & \frac{n-1}{\lambda(1-\alpha)(c_h - c_i^*)} - \frac{(n-1)(n-2)}{[\lambda(1-\alpha)(c_h - c_i^*)]^2} \\ & + \frac{(n-1)(n-2)(n-3)}{[\lambda(1-\alpha)(c_h - c_i^*)]^3} - \cdots \\ & + (-1)^{n-3} \frac{(n-1)!}{[\lambda(1-\alpha)(c_h - c_i^*)]^{n-2}} \\ & + (-1)^{n-2} \frac{(n-1)![1 - e^{-\lambda(1-\alpha)(c_h - c_i^*)}]}{[\lambda(1-\alpha)(c_h - c_i^*)]^{n-1}}. \end{aligned} \tag{10}$$

Finally, with post-auction cost uncertainty and the uniform distributions for c_i^* and w_i, the dominant strategy bid and cost reduction function for CARA bidders in the second-price auction is

$$b_2^A(c_i^*) = c_i^* + \frac{h(\xi^o)}{1-\alpha} - \xi^o + \frac{1}{\lambda(1-\alpha)} \ell n X. \tag{11}$$

Bid functions (6)–(8) and (11) are strictly increasing in base cost, c_i^*. This implies the second testable implication of the model.

HYPOTHESIS 2. *Contracts will be awarded to the bidders with lowest base costs*.

In other words, the model predicts there will be no adverse selection costs. This reflects the risk preference homogeneity (or ‘‘symmetry’’) assumption of the theory *except in the case of second-price auctions of contracts with no post-auction cost uncertainty* where the prediction is independent of agents' unobserved risk attitudes. This independence is a principal reason why we incorporated second-price auctions in our experimental design: we can use the risk-attitude-independent, dominant strategy predictions for the second-price auction with no post-auction cost uncertainty as a calibration for bidder behavior in the other types of experiments.

Equations (6) and (7) also imply that contract bids are lower in the second-price auction than in the first-price auction. In itself, this does not mean that expected procurement costs are predicted to be lower in the second-price auction than in the first-price auction because the bid price of the contract is the second-lowest bid, not the lowest bid, in the second-price auction. We show in the Appendix that bid functions (6) and (7) imply the following expected procurement payments for risk neutral agents in the first- and second-price auctions and all agents in second-price auctions with no post-auction cost uncertainty:

$$EP_1^N = EP_2^N = \frac{n-1+\alpha}{n+1} c_\ell + \frac{2-\alpha}{n+1} c_h + h(\xi^o) - \xi^o. \tag{12}$$

The relationships between expected procurement costs and the cost-sharing parameter, α, depend on the values of n, c_ℓ, c_h, and α, and on $h(\cdot)$. In designing our experiments, we selected a functional form for $h(\cdot)$ and values of the parameters that yield sharp predictions. Our design uses $h(\xi) = 0.25\xi^2$, $c_\ell = 5$, $c_h = 15$, and $n = 4$. These design specifications and equations (4) and (12) imply the following procurement cost equation for the two auctions:

$$EP_1^N = EP_2^N = 8 - 2\alpha + \alpha^2. \tag{13}$$

If there *is* post-auction cost uncertainty and (CARA) agents are risk averse then expected procurement payments for second-price auctions of contracts are

$$EP_2^A = \frac{n-1+\alpha}{n+1} c_\ell + \frac{2-\alpha}{n+1} c_h + h(\xi^o) - \xi^o + \frac{1}{\lambda} \ell n X, \tag{14}$$

where X, defined in Eq. (9), is the increment to risk averse equilibrium bids due to post-auction cost uncertainty. If (CARA) agents are risk averse then expected procurement payments for first-price auctions of contracts are

$$EP_1^A = c_\ell + \frac{c_h - c_\ell}{n+1} + h(\xi^o) - \xi^o + \frac{1}{\lambda}\ell n X - \frac{1}{\lambda} E_{C_1}(\ell n Y), \quad (15)$$

where Y is defined in Eq. (10) and $E_{C_1}(\cdot)$ denotes expected value using the density function for the first order statistic of the n-sample of base costs (defined in Eq. (a.9) of the Appendix).

The risk neutral expected procurement payment, Eq. (13), is invariant with post-auction cost uncertainty. The CARA risk averse expected procurement payments for second- and first-price auctions, Eqs. (14) and (15), are increasing in X; hence these expected payments are higher with post-auction cost uncertainty than with certain costs. These properties give us the third testable implication of the model.

HYPOTHESIS 3. *Expected procurement payments for first- and second-price auctions of contracts are not lower with post-auction cost uncertainty than with certain costs*.

Additional testable implications of the model can be efficiently extracted from numerical solutions of the expected procurement payment equations, (13)–(15). The solutions are presented in Table I. The second ($\lambda = 0$) column of Table I reports expected procurement payments for risk neutral agents. The third through eighth columns of Table I report expected procurement payments for agents with various CARA risk attitude parameters, $\lambda > 0$. The expected procurement payments for second-price auctions with certain costs are independent of the agents' risk attitudes. This independence is a principal reason why we incorporated second-price auctions in our experimental design.

The patterns exhibited by the expected procurement payments in Table I provide additional testable implications of the model. Rows four through six of Table I show that, in the first-price auction environment, expected procurement payments vary inversely to the cost-sharing rate, α, for all risk attitude parameters, $\lambda \geq 0$, when there is post-auction cost uncertainty. This gives us:

HYPOTHESIS 4. *With post-auction cost uncertainty*, *expected procurement payments for first-price auctions of contracts decrease with increases in the cost-sharing rate*.

Note from the top three rows of Table I that the model does not give us a similar prediction for first-price auctions in the certain cost environment.

TABLE I
Expected Procurement Payments

λ:	0	1	2	10	20	100	1000
First price auction with certain costs							
$\alpha = 0$	8.00	7.22	6.89	6.33	6.20	6.06	6.01
$\alpha = .3$	7.49	7.05	6.83	6.38	6.27	6.14	6.10
$\alpha = .85$	7.02	7.00	6.97	6.88	6.83	6.76	6.73
First price auction with uncertain costs							
$\alpha = 0$	8.00	8.10	8.24	8.44	8.47	8.50	8.50
$\alpha = .3$	7.49	7.52	7.61	7.78	7.81	7.83	7.84
$\alpha = .85$	7.02	7.02	7.02	7.05	7.07	7.09	7.10
Second price auction with certain costs							
$\alpha = 0$	8.00	8.00	8.00	8.00	8.00	8.00	8.00
$\alpha = .3$	7.49	7.49	7.49	7.49	7.49	7.49	7.49
$\alpha = .85$	7.02	7.02	7.02	7.02	7.02	7.02	7.02
Second price auction with uncertain costs							
$\alpha = 0$	8.00	8.88	9.35	10.11	10.27	10.44	10.49
$\alpha = .3$	7.49	7.96	8.27	8.88	9.03	9.18	9.23
$\alpha = .85$	7.02	7.05	7.07	7.20	7.26	7.35	7.39

Note. α = the cost sharing rate, λ = the coefficient of constant relative risk aversion, and $\lambda = 0$ denotes risk neutrality.

In contrast, the bottom six rows of Table I yield monotonic results for both cost environments for second-price auctions. This gives us:

HYPOTHESIS 5. *With certain costs or with post-auction cost uncertainty, expected procurement payments for second-price auctions of contracts decrease with increases in the cost-sharing rate.*

Comparison of the top six rows with the bottom six rows of Table I yields predictions of how expected procurement payments vary with the market institution. Thus we have:

HYPOTHESIS 6. *With certain costs or with post-auction cost uncertainty, expected procurement payments are not higher for first-price auctions than for second-price auctions of contracts.*

Finally, Table I provides numerical predictions of procurement payments for both market institutions. We will use the predictions in rows seven through nine and the risk neutral ($\lambda = 0$) predictions in the other parts of Table I as a theoretical baseline in some of our analysis of data from the experiments.

TABLE II
Experimental Design

Auction (contract)	Certain costs	Uncertain costs	Auction (contract)
S.P. I ($\alpha = 0$)	4 experiments	4 experiments	S.P. V ($\alpha = 0$)
F.P. II ($\alpha = 0$)	4 experiments	4 experiments	F.P. VI ($\alpha = 0$)
F.P. III ($\alpha = .30$)	4 experiments	2 experiments	F.P. VII ($\alpha = .30$)
F.P. IV ($\alpha = .85$)	4 experiments	4 experiments	F.P. VIII ($\alpha = .85$)

Note. F.P. = first price, S.P. = second price, and α = reimbursal (repayment) rate for cost overruns (savings).

3. EXPERIMENTAL DESIGN

We report a total of 30 experiments, assigned to contracting institutions and cost environments as listed in Table II. Each experiment was conducted with four subjects recruited from undergraduate economics classes at the University of Arizona (U of A). Each subject had participated in at least one other economics experiment at the U of A; however, no subjects repeated in our experiments.[1] Subjects were paid either $3.00 or $5.00 cash upon arriving at the room on time, the amount depending upon whether they were recruited for experiments expected to require two or three hours to complete.

The following experimental design features were common to all of the experiments. Subjects were seated at desks and randomly assigned to four seller positions in the market. Written instructions were distributed and also read aloud. An appendix containing the instructions is available from the authors. The subjects were told that they would participate as sellers in a series of auctions for the right to sell one unit of a commodity to the buyer (experimenter) in each period. They were told, in detail, the nature of the cost and payment institutions in which they would participate. Specific details were given as to what kinds of information would and would not be made public. ‘‘Total Cost’’ to the winning bidder in each period consisted of two or three parts, depending on whether or not the experiment contained an uncertain component of cost. In all experiments, bidders were informed, in nontechnical language, that in each period each seller would privately and individually receive an envelope containing a new draw, with replacement, from a discrete (one-cent increment) uniform

[1] In terms of the subjects’ comprehension of the mechanics of the experiment (filling out the bid forms, completing the accounting), we saw no need to go to a ‘‘super-experienced’’ subject pool. There was a single subject who was unable to figure out the accounting computations. That experiment was terminated after a few periods, and the data are not included here.

distribution from E$5.00 to E$15.00, where E$ denotes ‘‘experimental dollars.’’ This draw was known as the ‘‘Base Cost’’ and represented the c_i^* term of Eq. (1).

The subjects encountered the laboratory version of the moral hazard problem faced by winning bidders. In the markets reported here, winning bidders were required to choose a ‘‘Discretionary Cost Reduction’’ level (ξ_i in Eq. (1)) for a ‘‘Cost Reduction Fee’’ ($h(\xi_i)$). The cost reduction itself *did*, and the cost reduction fee *did not*, figure into the accounting cost revenue-adjustment component of the payment schemes of the cost-sharing contracts. Thus the cost reduction fee is the induced value of the effort cost that must be incurred in order to reduce observable costs.[2] The parameterization $h(\xi_i) = 0.25(\xi_i)^2$ was used in all experiments, with sellers restricted to choices of ξ_i between E$0.00 and E$4.00 in $0.25 increments. Finally, in those experiments that included uncertain costs all subjects were told that the winning bidder was to be handed a red envelope in which a ‘‘Random Cost Adjustment’’ had been drawn from a discrete (E$0.01 increment) uniform distribution from −E$2.50 to +E$2.50. The same sequence of draws of base costs and random cost adjustments for periods 1−20 were used in every experiment. An appendix containing these values is available from the authors. These cost values were generated from the advertised uniform distributions. Subjects were informed that the cost draws had already occurred.

The instructions for the experiments with cost-sharing contracts used the concept of a ‘‘Payment Adjustment’’ to explain this type of contract to the subjects. The subjects were first introduced to the idea of a ‘‘Cost Overrun’’ (total cost greater than the bid price) and a ‘‘Cost Savings’’ (total cost less than the bid price). The payment adjustment was explained as a fixed percentage (30 or 85%) of the cost overrun or saving. The subjects were then told that the payment to the winning bidder would consist of two parts, the bid price plus the payment adjustment. We chose 0.30 and 0.85 as values for the cost-sharing parameter, α, for the following reasons. When compared with the $\alpha = 0$ experiments, these two values of α are well spaced across the range 0 to 1. In addition, the $\alpha = 0.85$ value corresponds to the cost-sharing rule in some U.S. military procurement contracts.

During the course of the instructions, and then during the experiments themselves, some information was publicly known to all participants, some was private information, and some was known only by the experimenter. The information that was either common knowledge from the beginning or publicly announced as it developed included the probability distributions on c_i^* and w_i, the winning bid, the identification number of the winning

[2] The experimental technique of ‘‘induced valuation’’ is explained in Smith (1976).

bidder, the formula for defining payments and earnings under the appropriate institution, the actual payment made to the winning bidder, and the cost and fee structure of the discretionary cost reduction decision. In the second-price auctions, bidders were informed of the identification number of the second-lowest bidder in addition to the amount of the second-lowest bid (which was the payment in that institution). This information announcement was based upon a hypothesis as to what disclosures might be required by the government if a second-price contracting process were to be implemented. Individually realized base costs, bids of the ‘‘losing bidders’’ (except for the second-lowest bid in the second-price auctions), the actual discretionary cost reduction decision of the winning bidder, the actual realization of the uncertain cost random variable, and individual earnings were all private information.

Bidders did not know the identity of the final period (period 20). It was, however, common knowledge that the final period had been chosen in advance and that the experiment would proceed for no more than 30 periods. The experimenters answered clarifying questions and double-checked the arithmetic of all winning bidders. However, it was made clear that normative questions (such as ‘‘What is a good bid?’’) would not be answered. In all of the experiments, each bidder was given an initial endowment of E$5.00 to cover losses that could be incurred, and hence protected against bankruptcy complications. This E$5.00 endowment was in addition to the participation fee paid in cash at the beginning of the experiment. All sellers were informed of this and it appeared on each ‘‘Seller’s Record Sheet’’ in the first period.

Finally, we encountered a potential problem with the cost-sharing contracts in that the expected earnings to the winning bidder dropped dramatically as α increased. Therefore, we were faced with either (a) leaving the payoff structure identical across all treatments and risking loss of saliency from low rewards in the experiments with cost-sharing contracts, or (b) attempting to increase the expected earnings in the cost-sharing contract experiments by increasing the conversion ratio of ‘‘Experimental Dollars’’ to U.S. cash dollars (which was one-to-one in the second-price and first-price experiments with certain costs and with $\alpha = 0$). We chose the second approach. The various conversion ratios are listed in Table III.[3] The

[3] Cox and Isaac (1987) report no differential effects of various (salient) levels of conversion ratios in experiments looking at incentive regulatory mechanisms, while Grether (1992) and Cox and Grether (1996) report some changes in behavior when rewards become nonsalient. Of course, for the experiments reported here, the precise effect of altering conversion ratios in order to maintain saliency is an empirical question open to investigation by the motivated skeptic. It should also be noted that without these conversions, the subjects in the experiments with cost-sharing contracts would have earned considerably less money than those in the experiments with fixed-price contracts.

TABLE III
Exchange Rates: 1 Experimental Dollar = $\$X$ U.S.

Auction (contract)	Certain costs	Uncertain costs	Auction (contract)
S.P. I ($\alpha = 0$)	$1.00	$1.00	S.P. V ($\alpha = 0$)
F.P. II ($\alpha = 0$)	$1.00	$1.00	F.P. VI ($\alpha = 0$)
F.P. III ($\alpha = .30$)	$1.50	$1.50	F.P. VII ($\alpha = .30$)
F.P. IV ($\alpha = .85$)	$3.00	$2.00	F.P. VIII ($\alpha = .85$)

Note. F.P. = first price, S.P. = second price, α = reimbursal (repayment) rate for cost overruns (savings).

average subject in our experiments earned $14.42 cash, with the *per experiment* average ranging from $8.38 to $21.25. (This does not include the up-front participation fee, nor does it include the earnings from the two F.P. VII experiments in which, as will be discussed below, bankruptcy was a problem.) Additional details of our experimental procedures are contained in an appendix available from the authors.

4. EXPERIMENTAL RESULTS

Given the possibility of disequilibrium in the early periods, the data reported in tables is for the last 10 periods in each experiment. We report average deviations between observed and theoretically predicted procurement payments and results from tests of theoretical predictions. We also compare several measures of cost and efficiency for all of the procurement auctions.

A. Observed and Predicted Procurement Payments

Table IV presents quantitative measures of the predictive accuracy of the risk neutral special case of the model developed in Section 2. The middle column in the table presents the average over the last 10 periods in all of the experiments in a treatment of the differences between actual and predicted risk neutral procurement payments. The last column of Table IV presents standard deviations for these differences. Calculation of these standard deviations takes (the last 10 periods of) an experiment as an observation; hence these standard deviations are calculated for four observations. The absolute values of the ratios of the averages to their standard deviations are less than 1.5 for all treatments except F. P. II and F.P. III. The absolute values of these ratios are greater than 2.8 for F.P. II and F.P. III. Hence at conventional (5 and 10%) significance levels, t-tests lead to the conclusion that the risk neutral model's procurement payment predictions are not rejected for five of the eight experiments. We did not calculate the standard deviation for F.P. VII because there were only two experiments in this treatment. The t-tests for F.P. II and F.P. III imply rejection of the payment predications of the risk neutral model. Negative differences between observed and predicted risk neutral payments are predicted by (CARA) agent risk aversion, as shown in the first three rows of Table I. Deviations from risk neutral *revenue* predictions, in the direction consistent with bidder risk aversion, has previously been observed in first-price sealed-bid *seller's* auctions (Cox *et al*., 1982a; Cox *et al*., 1988; Isaac and Walker, 1985).

B. Tests of Market Predictions

We test several of the hypotheses that are accessible with our data. The first is that the discretionary cost reduction will be a discrete approximation of $g(1-\alpha)$, and that the amount of this cost reduction will be inversely related to α, as in Hypothesis 1 in Section 2. The predicted cost reductions are contained in Table V. We report nonunique predicted cost reduction amounts in those cases where the profit difference between two admissible discrete cost reduction choices is less than E$0.02. Note that the predicted cost reductions are the same for the certain and uncertain cost treatments with the same value of α. The third column in Table V reports the average actual discretionary cost reduction in (the last 10 periods of all experiments in) each treatment. Standard deviations, with an experiment treated as one observation, are reported in parentheses. Two

TABLE IV
Deviations between Observed and Predicted Risk Neutral Procurement Payments
(Final 10 Periods; Experimental Dollars)

Treatment	Average actual minus pred. payment	S.D. of difference[a]
Certain costs		
S.P. I ($\alpha = 0$)	0.20	0.40
F.P. II ($\alpha = 0$)	−0.56	0.17
F.P. III ($\alpha = .30$)	−0.55	0.19
F.P. IV ($\alpha = .85$)	0.20	0.14
Uncertain costs		
S.P. V ($\alpha = 0$)	0.66	0.74
F.P. VI ($\alpha = 0$)	−0.05	0.30
F.P. VII ($\alpha = .30$)	−0.80	**[b]
F.P. VIII ($\alpha = .85$)	−0.04	0.12

[a] One experiment = one observation.
[b] Only two experiments.

results are apparent. First, the average actual discretionary cost reductions are inversely related to α; thus the predicted moral hazard effects of cost-sharing contracts are observed in our experiments. Second, all of the average actual cost reductions are much less than 1.5 standard deviations from their predicted values. We conclude that the theory predicts the subjects' choice of discretionary cost reduction reasonably accurately. Finally, the fourth column in Table V illustrates the incidence of moral hazard costs of cost-sharing contracts by expressing the actual cost reduction as a percentage of the optimal cost reduction. Note that for $\alpha = 0$, the actual cost reduction is more than 95% of the optimal level of cost reduction for both certain and uncertain cost treatments. In comparison, for $\alpha = .85$ the actual cost reduction is 7.5% of the optimal level in the certain cost treatment and 23.2% in the uncertain cost treatment.

We next test Hypothesis 2, that contracts will be awarded to the bidders with the lowest base costs; that is, that there are no adverse selection costs. In the case of the first-price auction, this prediction requires a (symmetry) assumption that all the bidders have the same risk preferences. In the case of the second-price auction, the prediction of no adverse selection costs requires a symmetry assumption in the uncertain cost treatment but does

TABLE V
Discretionary Cost Reductions
(Final 10 Periods: Experimental Dollars)

Treatment	Predicted cost reduction	Actual average cost reduction[a]	Average as % of optimal reduction
Certain costs			
F.P. II ($\alpha = 0$)	2.00	1.91	95.5
		(0.21)	
F.P. III ($\alpha = 0$)	1.25 or 1.50	1.34	67.2
		(0.07)	
F.P. IV ($\alpha = .30$)	0.25 or 0.50	0.15	7.5
		(0.10)	
Uncertain costs			
F.P. VI ($\alpha = 0$)	2.00	1.94	97.2
		(0.12)	
F.P. VII ($\alpha = .30$)	1.25 or 1.50	0.95	47.5
		(**)[b]	
F.P. VIII ($\alpha = .85$)	0.25 or 0.50	0.46	23.2
		(0.32)	

[a] Standard deviations in parentheses; one experiment = one observation.
[b] Only two experiments.

not require a symmetry assumption in the certain cost treatment. As explained in Section 2, this property of the second-price auction is a principal reason for its inclusion in our experimental design.

The actual adverse selection costs in our experiments are reported in Table VI. The average observable cost excess over low base cost for the second-price auction was E$0.05 in the certain cost treatment and E$0.10 in the uncertain cost treatment. Neither of these figures is significantly different from zero on the basis of a *t*-test. The proportion of contracts that was awarded to the low-cost bidders by second-price auctions was 0.9 in the certain cost treatment and 0.8 in the uncertain cost treatment. The 0.9 figure is not significantly different, and the 0.8 figure is significantly different, from 1 on the basis of a *t*-test. We conclude that asymmetry of risk preferences in our subjects marginally increased the proportion of auctions in which adverse selection occurred but had an insignificant effect on average cost.

Next, consider the adverse-selection costs for first-price auctions with three different cost-sharing parameters that are reported in Table VI. For

TABLE VI
Adverse Selection Costs
(Final 10 Periods; Experimental Dollars)

Treatment	Proportion of contracts awarded to low cost bidders[a]	Average observed cost excess over low base cost[a]
Certain costs		
S.P. I ($\alpha = 0$)	0.90	0.05
	(0.14)	(0.08)
F.P. II ($\alpha = 0$)	0.92	0.03
	(0.10)	(0.04)
F.P. III ($\alpha = .30$)	0.92	0.06
	(0.05)	(0.07)
F.P. IV ($\alpha = .85$)	0.85	0.12
	(0.17)	(0.15)
Uncertain costs		
S.P. V ($\alpha = 0$)	0.80	0.10
	(0.08)	(0.07)
F.P. VI ($\alpha = 0$)	0.80	0.05
	(0.14)	(0.03)
F.P. VII ($\alpha = .30$)	0.75	0.48
	(**)[b]	(**)[b]
F.P. VIII ($\alpha = .85$)	0.85	0.33
	(0.17)	(0.38)

[a] Standard deviations in parentheses; one experiment = one observation.
[b] Only two experiments.

the certain cost treatment, the proportion of contracts awarded to the low-cost bidders varied from 0.92 to 0.85 as α varied from 0 to 0.85. None of these proportions is significantly different from 1. With uncertain costs, the proportions are 0.80, 0.75, and 0.85 when α is 0, 0.30, and 0.85. None of these proportions is significantly different from 1. With certain costs, the average cost excess for first-price auctions varies between E$0.03 and E$0.12; none of these amounts is significantly different from zero. With uncertain costs, the average cost excesses are E$0.05, E$0.48, and E$0.33 when α is 0, 0.30, and 0.85. The excess cost figures for cost-sharing proportions of 0.30 and 0.85 are noticeably higher with uncertain costs than they are with certain costs; however, because of increased variability across experiments, they are not (known to be) significantly different from zero for the uncertain cost treatments.[4]

Comparing the observations reported in Tables V and VI, we conclude that the moral-hazard costs of cost-sharing contracts are much more important than are their adverse-selection costs. This difference is predicted by the theoretical model in Section 2.

Table VII presents tests of Hypotheses 3–6 concerning expected procurement payments. This table reports the results of *t*-tests based on alternative independence assumptions. The test statistics reported in the third column of Table VII are based on the assumption that all experimental periods are independent. The last column in the table reports test statistics based on the weaker independence assumption, used elsewhere in this paper, that all experiments in a treatment are independent. For the certain cost treatments, both test statistics imply rejection of the hypothesis that the second-price auction yields lower average payments (see row 1 in Table VII); the second-price auction yields significantly higher average procurement payments, as predicted by the model for positive CARA coefficients. The second-price auction also has higher average procurement payments than the first-price auction in the uncertain cost treatment; the difference here is significant by the independent-periods test statistic but it is insignificant by the independent-experiments test statistic. Test statistics are presented for comparison of the fixed-price contracts with both the $\alpha = 0.30$ and the $\alpha = 0.85$ cost-sharing contracts awarded with first-price auctions. All of the ($\alpha = 0$ minus $\alpha > 0$) average payment differences are significantly positive, for both certain and uncertain cost treatments, by the independent-experiments test statistic. Thus the theo-

[4] Each of the percentages given in Table VI is significantly different from what would be expected from an equal probability random process (at a 95% confidence level).

TABLE VII
Procurement Payment Pairwise Treatment Comparisons Difference in Means Test
(Final 10 Periods; Experimental Dollars)

Comparison	Average monetary difference	t-statistic[a]	t-statistic[b]
Certain costs			
S.P.I ($\alpha = 0$)−F.P.II ($\alpha = 0$)	0.73	2.60[c]	3.16[c]
F.P.II ($\alpha = 0$)−F.P.III ($\alpha = .30$)	0.49	1.90[c]	3.80[c]
F.P.II ($\alpha = 0$)−F.P.IV ($\alpha = .85$)	0.27	1.04	2.43[c]
F.P.III ($\alpha = .30$)−F.P.IV ($\alpha = .85$)	−0.22	−0.80	−1.87
Uncertain costs			
S.P.V ($\alpha = 0$)−F.P.VI ($\alpha = 0$)	0.68	2.30[c]	1.70
F.P.VI ($\alpha = 0$)−F.P.VII[d] ($\alpha = .30$)	1.30	4.27[c]	3.46[c]
F.P.VI ($\alpha = 0$)−F.P.VIII ($\alpha = .85$)	1.17	4.16[c]	7.34[c]
F.P.VII[d] ($\alpha = .30$)−F.P.VIII ($\alpha = .85$)	−0.13	−0.34	−0.41
Certain vs. uncertain costs			
S.P.I ($\alpha = 0$)−S.P.V ($\alpha = 0$)	−0.46	−1.38	−1.07
F.P.II ($\alpha = 0$)−F.P.V ($\alpha = 0$)	−0.51	−2.16[c]	−2.98[c]
F.P.III ($\alpha = .30$)−F.P.VII[d] ($\alpha = .30$)	0.30	0.89	0.89
F.P.IV ($\alpha = .85$)−F.P.VIII ($\alpha = .85$)	0.39	1.29	2.85[c]

[a] Based on sample size of 40, presuming independence across periods.
[b] Based on sample size of 4, *not* presuming independence across periods.
[c] Significant at 90% confidence level.
[d] F.P.VII has only two experiments, thus reducing the sample size to 20 in column 3 and 2 in column 4.

retical prediction that fixed-price contracts are more expensive for the buyer is clearly supported by this test. The other test-statistic, based on the independent-periods assumption, implies significance of the positive differences between fixed-price and cost-sharing contract average payments in three out of the four comparisons. Finally, comparison of the $\alpha = 0.30$ and $\alpha = 0.85$ cost-sharing contracts yields insignificant (negative) average payment differences, whereas the theory implies positive differences.

Table VII also presents test statistics for average payment differences between certain and uncertain cost experiments with the same value of the cost-sharing parameter. The theory predicts that if the bidders are risk neutral then these average payment differences are zero and if (CARA) bidders are risk averse then the differences are negative. The second-price auction difference (S.P. I−S.P. V) is insignificantly negative. One-third or two-thirds (depending on the choice of test statistic) of the first-price auction payment differences on the last three rows of Table VII are significant. But these payment differences are both positive and negative; therefore they cannot be explained by subjects' risk aversion.

C. Cost and Efficiency Comparisons

Monitored or observable costs can differ from true economic (minimum) costs because of the adverse-selection and moral-hazard problems. A successful bidder is provided an opportunity to lower his observed cost by an amount ξ_i by incurring an unobservable effort cost in the amount $h(\xi_i)$. Table VIII presents, for each experimental treatment, the average (Pareto) *optimal* observable cost, the average *profit-maximizing* observable cost, and the average *actual* observable cost. All of these observable cost measures exclude effort cost. ''Optimal cost'' equals the lowest (across bidders) base cost plus the realization of the uncertain cost (random variable) minus the *optimal* amount of discretionary cost reduction; thus it presumes zero adverse-selection and moral-hazard costs. ''Profit-maximizing cost'' equals the lowest base cost plus the realization of the uncertain cost minus the *profit-maximizing* amount of discretionary cost reduction. Thus the difference between optimal cost and profit-maximizing cost is the profit-maximizing level of moral-hazard cost. ''Actual cost'' is the amount of (observable) cost that resulted from the subjects' decisions and the

TABLE VIII
Average Cost Measures
(Final 10 Periods; Experimental Dollars)

Treatment	Average opt. observed cost	Average profit-max. observed cost	Average act. observed cost[a]
Certain costs			
S.P.I ($\alpha = 0$)	5.02	5.02	5.19 (1.18)
F.P.II ($\alpha = 0$)	5.02	5.02	5.13 (1.34)
F.P.III ($\alpha = .30$)	5.02	5.64	5.73 (1.24)
F.P.IV ($\alpha = .85$)	5.02	6.64	6.99 (1.32)
Uncertain costs			
S.P.V ($\alpha = 0$)	4.83	4.83	5.48 (1.35)
F.P.VI ($\alpha = 0$)	4.83	4.83	4.93 (1.27)
F.P.VII[b] ($\alpha = .30$)	4.83	5.46	6.46 (**)[b]
F.P.VIII ($\alpha = .85$)	4.83	6.46	6.70 (1.61)

[a] Standard deviations in parentheses; one experiment = one observation.
[b] Only two experiments.

realization of uncertain cost (if any) in an experiment; it includes the actual adverse-selection and moral-hazard costs. The optimal and profit-maximizing average costs in Table VIII are identical when $\alpha = 0$ and the excess of the latter over the former varies directly with α. This is consistent with the moral-hazard cost predictions of the theory (see statement (5) and the accompanying discussion in Section 2). Actual average cost exceeds profit-maximizing average cost in every treatment, but none of the differences are significant on the basis of a t-test. The actual average costs vary directly with α, as do the profit-maximizing average costs predicted by the model.

Table IX presents empirical results on cost overruns and the incidence of bids below base cost for the first-price auction experiments. A ‘‘cost overrun’’ is defined to occur if the winning bidder’s actual cost (as in Table VIII) exceeds his bid (i.e., the bid price of the contract). In the certain cost experiments, there was only one cost overrun (in F.P. IV) in 120 contract auctions (i.e., 3 F.P. treatments $\times$ 4 experiments per treatment $\times$ (the last) 10 periods per experiment). This occurred despite the fact that 28 and 25% of all bids were below base cost in F.P. II and F.P. III. The below-base-cost bidding in these experiments apparently resulted from competitive pressure (to bid so as) to transfer part of planned discretionary cost reduction

TABLE IX
Cost Overruns and Below Cost Bidding
(Final 10 Periods)

Treatment	Cost overruns for winning bidders (%)[a]	Bids at or below base cost for all bidders (%)
Certain costs		
F.P.II ($\alpha = 0$)	0 (0.00)	28.1
F.P.III ($\alpha = .30$)	0 (0.00)	25.0
F.P.IV ($\alpha = .85$)	2.5 (0.05)	3.1
Uncertain costs		
F.P.VI ($\alpha = 0$)	0 (0.00)	11.9
F.P.VII[b] ($\alpha = .30$)	45.0 (0.21)	57.5
F.P.VIII ($\alpha = .85$)	27.5 (0.18)	18.8

[a] Standard deviations in parentheses; one experiment = one observation.
[b] Only two experiments.

to the buyer in order to try to land the contract. Below-base-cost bidding decreased significantly (to 3.1%) when α was increased to 0.85 in F.P. IV.

The risk-sharing parameter, α, had a dramatic effect on cost overruns in the uncertain cost experiments in Table IX. There were zero cost overruns in F.P. VI (with $\alpha = 0$) but cost overruns in 45 and 27.5% of the contract auctions in F.P. VII (with $\alpha = 0.30$) and F.P. VIII (with $\alpha = 0.85$) respectively. Cost overruns in our experimental design can arise either from too-low bids or from relatively high random cost realizations. But it is clear from Table IX that the introduction of uncertain costs, in the context of auctions of cost-sharing contracts, led to higher percentages of bids at or below base costs (57.5 > 25.0 and 18.8 > 3.1). This is contrary to expectations if bidders are risk neutral or risk averse. Though based on only two experiments, it is the large number of cost overruns in the F.P. VII ($\alpha = 0.30$) uncertain cost experiments which produced subject bankruptcies, to be discussed in the concluding section. The experimental result, of large numbers of cost overruns occurring with cost-sharing contracts, mirrors government contracting experience but is not addressed by existing theory.

Table X reports an allocative efficiency measure for all of the treatments. The reported overall (allocative) efficiency number for an experiment is the sum over all periods of the ratio of the lowest possible cost of fulfilling the contract to the actual cost of the low bidder (multiplied by 100).[5] Neither of the cost-sharing contracts performs as well as either of the fixed-price contracts in both the certain cost treatment and the uncertain cost treatment. The Wilcoxon rank sum test on the overall ranking suggests that the fixed-price contracts yielded greater allocative efficiency than the cost-sharing contracts at a significance level of .029 in a one-tailed test. To understand the sources of this efficiency loss, compare the fixed-price and $\alpha = .85$ cost-sharing contracts with uncertain costs awarded with first-price auctions. The fixed-price contracts yielded an efficiency rating of 98.8%, whereas the efficiency of the cost-sharing contracts was 85.8%. This translates into economic costs that exceed the minimum possible level in the amounts of E$0.06 and E$0.97, respectively. Because of the control exercised in our experiments, we can attribute these allocative inefficiencies to their causal sources. For the E$0.06 inefficiency in the fixed-price contract, approximately E$0.04 of this is due to the contract not going to the low cost firm (i.e., adverse-selection costs),

[5] The formula for the allocative efficiency calculation is $[\sum_{t=11}^{20} N_t/D_t]\,100$, where $N_t \equiv$ the lowest base cost in period t minus the optimal discretionary cost reduction in period t plus the fee for the optimal discretionary cost reduction in period t plus the random cost adjustment in period t; and $D_t \equiv$ the actual base cost in period t minus the actual discretionary cost adjustment in period t plus the fee for the actual discretionary cost adjustment in period t plus the random cost adjustment in period t.

TABLE X
Procurement Payments and Overall Efficiencies
(Final 10 Periods, Experimental Dollar)

Treatment	Overall efficiency (%)[a]	Rank	Average procurement payment[a]	Rank
Certain Costs				
S.P.I ($\alpha = 0$)	98.9	1	8.18	4
	(1.2)		(0.40)	
F.P.II ($\alpha = 0$)	98.8	2	7.45	3
	(1.2)		(0.17)	
F.P.III ($\alpha = .30$)	96.9	3	6.96	1
	(1.2)		(0.19)	
F.P.IV ($\alpha = .85$)	86.0	4	7.18	2
	(1.8)		(0.14)	
Uncertain Costs				
S.P.V ($\alpha = 0$)	94.0	2	8.64	4
	(2.1)		(0.74)	
F.P.VI ($\alpha = 0$)	98.8	1	7.96	3
	(1.0)		(0.30)	
F.P.VII ($\alpha = .30$)	86.0	3	6.66	1
	(**)[b]		(**)[b]	
F.P.VIII ($\alpha = .85$)	85.8	4	6.79	2
	(3.4)		(0.12)	

[a] Standard deviations in parentheses; one experiment = one observation.
[b] Only two experiments.

and the remaining E$0.02 is due to non-optimal cost reduction decisions (i.e., moral-hazard costs). Neither of these is predicted. For the cost-sharing contract, almost E$0.34 of the inefficiency is due to adverse-selection costs, whereas the remaining E$0.63 is due to moral-hazard costs. In comparison, E$0.67 is the predicted moral-hazard cost resulting from profit maximization. From these numbers, it can be seen that the observed moral-hazard inefficiencies are close to the theoretical predictions. The relatively large losses due to adverse-selection costs are not predicted by (symmetric) theory. One possible explanation of the adverse-selection costs is that they are due to our use of *real* bidders with heterogeneous risk attitudes and/or heterogeneous expectations.

Figure 1 presents the average total efficiency loss for each treatment and its decomposition into adverse-selection and moral-hazard costs. Note that the moral-hazard cost monotonically increases with α for both the certain-cost first-price treatments (F.P. II, III, and IV) and the uncertain-cost first-price treatments (F.P. VI, VII, and VIII). This result is predicted by the theory presented in Section 2. Adverse-selection costs also increase monotonically with α in the certain cost experiments, but by much less

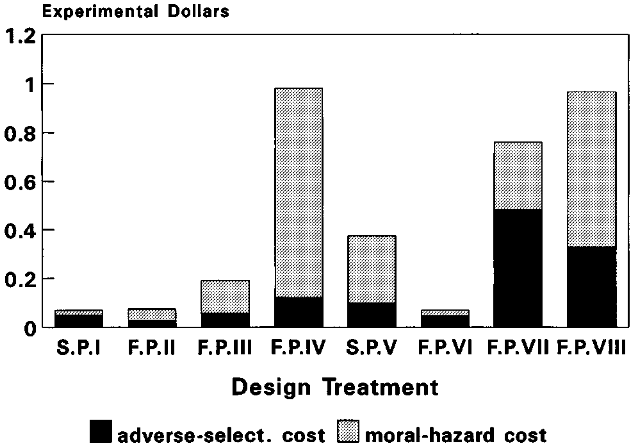

FIG. 1. Decomposition of Efficiency Losses (average by design treatment)

than moral-hazard costs. Finally, adverse-selection costs are higher for $\alpha > 0$ in the uncertain cost experiments than in the certain cost experiments. Adverse-selection costs are not predicted by the model developed in Section 2 (nor by any *symmetric* model).[6]

Table X presents rankings of the four types of contracts, for both certain and uncertain cost treatments, in terms of both allocative efficiency and average procurement payment. Perhaps the most dramatic observation regarding the performance of the four types of contracts is the near inversion in their rankings for the efficiency criterion and the minimum-payment criterion. Part of this divergence is predicted by the theory and part is not. The predicted part consists of: (a) statement (5) implies that discretionary cost reduction varies inversely to α (i.e., moral hazard cost varies directly with α); and (b) Table I implies that expected payments in the first-price and second-price auctions vary inversely with α. The unpredicted part of the empirical relation between allocative efficiency and average procurement payment is the generally inverse relationship between adverse selection costs and α that is illustrated in Fig. 1.

D. Tests of Individual Bid and Cost-Reduction Predictions

The individual bid data can be used to test the equilibrium choice and bid functions of Eqs. (6)–(11) and as further developed in Table I and the

[6] A *symmetric* model is one in which all of the bidders have the same risk preferences. The symmetry assumption characterizes almost all of the large literature on bidding theory. Notable exceptions are the heterogeneous bidders models (CRRAM and the log-concave model) developed in Cox *et al.* (1982a, 1982b, 1988).

Appendix. We can write a general ‘‘bid’’ function for estimation of the two equations in the form

$$b_{it} = a_i + \beta_i c_{it}^* + \theta_{it}, \tag{16}$$

where b_{it} is bidder i’s bid in period t, a_i is a constant, c_{it}^* is bidder i’s base cost in period t, and θ_{it} is random error. The β_i term picks up the slope relative to base cost, and the a_i term is a constant which incorporates both the bid function intercept *and* the constant term reflecting discretionary cost reduction $(h(\xi^o)/(1-\alpha) - \xi^o)$. Thus, this estimation is not simply a bid function, because it incorporates two decisions on the part of the bidder, discretionary cost reduction and amount bid. The predicted values of a_i and β_i vary with auction type, cost-sharing parameter α, and the presence or absence of post-auction cost uncertainty.

We estimated 120 separate equations, one for each bidder. The individual regression parameters are not as important for this analysis as are the summary implications for the equilibrium models. First, in both of the two second-price auction designs (S.P.I and S.P.V) the predicted value of β_i is 1, independent of the bidder’s risk preferences. In fact, we fail to reject the null hypothesis that $\beta_i = 1$ in 25 of 32 cases (all tests are at the 95% confidence level, and one-tail or two-tail as appropriate to the theory). In the remaining six designs (all with the first price institution) $\beta_i = 0.75$ is a Nash equilibrium prediction under the assumption of risk neutrality. We fail to reject $\beta_i = 0.75$ in only 28 of 88 cases. The rejection rates do not vary markedly by either cost-sharing parameter or by post-auction cost uncertainty condition (.75, .81, .68, .75, .38, and .56 in F.P. II, III, IV, VI, VII, and VIII respectively). Specifically, a difference in proportions test on the pooled rejection rates of 0.75 (no post-auction cost uncertainty) and .60 (post-auction cost uncertainty) cannot reject the hypothesis that the rejection proportions are the same for a 95% level of confidence.

When looking at hypothesis tests on the constant term, only S.P.I has a prediction $(a_i = -1)$ which is independent of risk attitudes. We fail to reject the null hypothesis that $a_i = -1$ in 12 of 16 cases. In the remainder of the seven designs, the prediction assumes risk neutrality and varies by auction type and cost-sharing parameter, but not by the presence or absence of post-auction cost uncertainty. Across 104 subjects, we fail to reject the hypothesis that a_i is as predicted by the risk neutral version of the relevant theory in 42 cases.

As mentioned, ‘‘bidders’’ here had to consider simultaneously a discretionary cost reduction problem and a bidding problem. Failures of the estimated parameters to conform to the predicted values may not be easily interpretable as an independent failure of the cost-reduction decision model or the bidding model alone.

The individual bid data can be used to shed more light on issues examined in the previous subsection, namely the effects on revenue of post-auction cost uncertainty and the concurrent role of risk aversion. For each bidder in each time period, we calculated the equilibrium risk-neutral bid and then calculated the bidding deviation (actual bid minus risk neutral predicted bid). Then, for each bidder, we calculated a simple score: we asked whether in a majority (11) of the periods the individual's bids were either higher or lower than predicted. Tracking these scores across experimental designs offers the following interesting comparisons. First, we compare the effect of auction rules for the designs with no post-auction cost uncertainty. For the case of the second-price auction (S.P.I) there is a dominant strategy prediction which is independent of risk attitudes. Only one of these sixteen bidders scored as having mostly negative deviations. On the other hand, when we switch to first-price auctions, again without post-auction cost uncertainty (F.P. II, F.P. III, and F.P. IV), the Nash model predicts negative deviations for risk averse bidders. Indeed, in these cases 23 of 48 bidders indicate negative deviations relative to the prediction; both the absolute proportion and the shift in proportion from the second-price auction seem to be consistent with a prediction for (at least some) risk-averse agents. A similar pattern can be seen by comparing F.P. II and F.P. VI. These are both first-price designs, and both have no cost-sharing ($\alpha = 0$) contracts. The only difference is that F.P. VI adds post-auction cost uncertainty. As mentioned above, the risk averse prediction for F.P. II is for negative deviations but, because of the post-auction cost uncertainty, risk averse bidders should have positive deviations in F.P. VI. Ten out of sixteen bidders have positive deviations in F.P. II, while fourteen of sixteen bidders have positive deviations in F.P. VI. Again the shift is in the direction predicted by a model of risk averse agents.

Things look very different for the first-price auctions with cost-sharing contracts. With no post-auction cost uncertainty, 17 of 32 bidders have negative deviations, 12 had positive deviations, and 3 split. Adding post-auction cost uncertainty should, as in the case of F.P. II and F.P. VI above, generate more positive bidder deviations if bidders are risk averse. Contrary to this expectation, in F.P. VII and F.P. VIII, out of 24 bidders, 16 were negative deviation bidders, 7 were positive deviation bidders, and 1 split. Thus in this one part of the design space, the pattern of deviations was the opposite of what we would have expected from the risk averse model.

In summary, looking at individual deviations in this way has allowed us to do the following. We used the risk-attitude-independent dominant strategy as a calibration for bidder behavior in other designs (most bidders tended to bid too high). We found that actual changes in bidding deviations were consistent with risk averse bidding models over most of the design space. However, bids in one area of the design space, first-price auctions with $\alpha = .30$ and .85 and with post-auction cost uncertainty, produced anomalous changes that could not be explained by risk aversion. This is consistent with the market price anomalies discussed earlier and reported in Table VII.

5. CONCLUDING REMARKS

The primary conclusion from the above analysis is that there is a fundamental trade-off between minimizing budgetary procurement expense and maximizing allocative efficiency. As highlighted by the rankings in Table X, the cost-sharing contracts are the least expensive and the least efficient. The lower efficiencies of the cost-sharing contracts are attributed to both moral hazard and adverse-selection costs. The lower procurement expense of the cost-sharing contracts results from bids that are low enough to more than offset the higher moral hazard and adverse selection costs of these contracts. Thus, it is clear that the goal of reducing procurement expense is best served by use of cost-sharing contracts. It is equally clear that doing so will lead to inefficiencies that manifest themselves as waste accompanied by documentable cost overruns and even bankruptcies. In other words, potentially embarrassing political ramifications are a necessary consequence of lowering procurement expense.

There are qualifications to our primary conclusion. Most obviously, it has only been demonstrated to hold for the contracting institutions that we studied. In addition, our results contain one significant anomaly which warrants caution. Specifically, the winning (low) bids under the cost-sharing contracts *decreased* when post-contracting cost uncertainty was introduced, contrary to theory. We leave an explanation of this phenomenon for future research. We also leave to future work one immediate extension of our experiments. Specifically, in the uncertain cost experiments with a 30% cost-sharing rate (F.P. VII), winning bids were so low that bankruptcies were quite common even though subjects were given an initial endowment to decrease the chance of this occurring. (This is the reason why only two experiments were run for this treatment.) Thus, it will be necessary to augment the cost-sharing contract institution with a bankruptcy rule. Other immediate extensions include replications for variations on the number of bidders, the reimbursal rate, the discretionary cost choice, and the distributions of both base costs and random cost shocks.

APPENDIX: PROCUREMENT AUCTION THEORY

First-Price Auctions. We begin with bidding theory for first-price sealed-bid auctions. Equations (1) and (3) in Section 2 give us the winning bidder's profit equation, conditional on the profit-maximizing choice of discretionary cost reduction (ξ^o) given by Eq. (5):

$$\pi_i = (1-\alpha)(b_i - c_i^* - w_i + \xi^o) - h(\xi^o). \tag{a.1}$$

Assume that the c_i^*, $i = 1, 2, \ldots, n$, are drawn independently from the distribution with c.d.f., $G(\cdot)$, on the support $[c_\ell, c_h]$ such that $c_h > c_\ell \geq 0$. Also assume that each bidder j, other than i, uses the strictly increasing, differentiable bid function, $b_1(c_j^*)$. Let $\gamma(b)$ be the inverse of the bid function, then $[1 - G(\gamma(b_i))]^{n-1}$ is the probability that a bid in the amount b_i by bidder i will be a winning bid. Let bidder i have von Neumann–Morgenstern utility function $u(\cdot)$, normalized such that $u(0) = 0$; then the expected utility of a bid in the amount b_i is

$$U(b_i) = \left[1 - G(\gamma(b_i))\right]^{n-1} E_W u(\pi_i). \tag{a.2}$$

Using (a.1), we see that the first order condition for a bid in the amount b_i^o to maximize (a.2) is

$$\begin{aligned} 0 &= U'(b_i^o) \\ &= \left[1 - G(\gamma(b_i^o))\right]^{n-1}(1-\alpha)E_W u'(\pi_i) \\ &\quad -(n-1)\left[1 - G(\gamma(b_i^o))\right]^{n-2} G'(\gamma(b_i^o))\gamma'(b_i^o)E_W u(\pi_i). \end{aligned} \tag{a.3}$$

If $\gamma(\cdot)$ is to be the inverse of a symmetric equilibrium bid function, it is necessary that $c_i^* = \gamma(b_i^o)$. Substituting c_i^* for $\gamma(b_i^o)$ and $1/b_1'(c_i^*)$ for $\gamma'(b_i^o)$ in (a.3), and solving for $b_1'(c_i^*)$ yields

$$b_1'(c_i^*) = \frac{(n-1)\left[1 - G(c_i^*)\right]^{n-2} G'(c_i^*) E_W u(\pi(c_i^*))}{(1-\alpha)\left[1 - G(c_i^*)\right]^{n-1} E_W u'(\pi(c_i^*))} \tag{a.4}$$

where

$$\pi(c_i^*) = (1-\alpha)(b_1(c_i^*) - c_i^* - w_i + \xi^o) - h(\xi^o). \tag{a.5}$$

Equation (a.4) is equivalent to Eq. (9) in McAfee and McMillan (1986). We now depart from their analysis in order to derive a closed form solution for our equilibrium bid function.

Substitute from our equation (a.5) into (a.4) and then integrate the result to obtain

$$[1 - G(c_i^*)]^{n-1} E_W u(\pi(c_i^*)) = -\int_{c_\ell}^{c_i^*} (1-\alpha)[1 - G(x)]^{n-1} E_W u'(\pi(x))\, dx + C. \quad \text{(a.6)}$$

The constant of integration, C, can be determined by noting that $1 - G(c_h) = 0$; hence

$$C = \int_{c_\ell}^{c_h} (1-\alpha)[1 - G(x)]^{n-1} E_W u'(\pi(x))\, dx. \quad \text{(a.7)}$$

Equations (a.6) and (a.7) imply

$$[1 - G(c_i^*)]^{n-1} E_W u(\pi(c_i^*)) = \int_{c_i^*}^{c_h} (1-\alpha)[1 - G(x)]^{n-1} E_W u'(\pi(x))\, dx. \quad \text{(a.8)}$$

Now assume that $G(\cdot)$ is the uniform distribution on $[c_\ell, c_h]$ and that the bidders are risk neutral; then (a.8) can be solved for the risk neutral equilibrium bid function, contained in Eq. (6) in the text. If $G(\cdot)$ is uniform on $[c_\ell, c_h]$ and all agents have constant absolute risk averse (CARA) preferences with coefficient $\lambda > 0$, then (a.8) can be solved for the (CARA) risk averse equilibrium bid function contained in text Eqs. (8)–(10).

The density function for the first order statistic (i.e., the lowest cost) for a sample of size n from the uniform distribution on $[c_\ell, c_h]$ is

$$f_{C_1}(c^*) = n\left[1 - \frac{c^* - c_\ell}{c_h - c_\ell}\right]^{n-1} \frac{1}{c_h - c_\ell}. \quad \text{(a.9)}$$

Hence the expected value of the lowest cost is

$$\int_{c_\ell}^{c_h} c^* f_{C_1}(c^*)\, dc^* = c_\ell + \frac{c_h - c_\ell}{n+1}. \quad \text{(a.10)}$$

Derivation of the equality in (a.10) involves substitution from (a.9) and integration by parts. To find the expected procurement payment for risk neutral agents in the first-price auction, we substitute the expected value of the lowest base cost given by (a.10) into the bid function, (6), and then substitute the result into the contract payment function, (2), using Eq. (1)

to get the expected procurement payment, EP_1^N, in the text Eq. (12). The expected procurement payment for (CARA) risk averse agents in the first-price auction, EP_1^A, is derived from Eqs. (1), (2), (8), and (a.9), and is presented in the text Eq. (15).

Second-Price Auctions. Now consider the case where the contract is awarded by means of a second-price sealed-bid auction. With this type of auction, the contract price is the second lowest bid. Knowing the form of the contract they will be awarded if successful, the agents choose their bids, b_i. Let the c.d.f., $H_i(y)$, represent the ith bidder's expectations about the random variable y, the lowest bid submitted by any of agent i's rivals. If it turns out that $y > b_i$, then bidder i's bid is the lowest and he is awarded the contract at the price y. If the realization is such that $y < b_i$, then bidder i is not awarded the contract. Given the normalization, $u_i(0) = 0$, the expected utility to bidder i of a bid in the amount b_i is

$$V(b_i) = \int_{b_i}^{\infty} E_W u_i\big((1-\alpha)(y - c_i^* - w_i + \xi^o) - h(\xi^o)\big)\, dH_i(y). \tag{a.11}$$

The first order condition for b_i^o to maximize (a.11) is

$$0 = V'(b_i^o) = -E_W u_i\big((1-\alpha)(b_i^o - c_i^* - w_i + \xi^o) - h(\xi^o)\big) H_i'(b_i^o) \tag{a.12}$$

or, assuming that $H_i'(b_i^o) > 0$,

$$0 = E_W u_i\big((1-\alpha)(b_i^o - c_i^* - w_i + \xi^o) - h(\xi^o)\big). \tag{a.13}$$

The bidder's dominant strategy bid function for the second-price auction is defined implicitly by (a.13). If all costs are certain ($w_i \equiv 0$), Eq. (a.13) becomes

$$0 = u_i\big((1-\alpha)(b_i^o - c_i^* + \xi^o) - h(\xi^o)\big). \tag{a.14}$$

Since $u_i(0) = 0$, Eq. (a.14) gives us the dominant strategy bid function contained in text equation (7). Alternatively, if bidder i is risk neutral then $u_i(\cdot)$ is linear and (a.13) becomes

$$\begin{aligned} 0 &= E_W\big[(1-\alpha)(b_i^o - c_i^* - w_i + \xi^o) - h(\xi^o)\big] \\ &= (1-\alpha)(b_i^o - Ew_i + \xi^o) - h(\xi^o). \end{aligned} \tag{a.15}$$

Since $E(w_i) = 0$, Eq. (a.15) also gives us bid function (7). Thus, (7) is the dominant strategy bid function if either all post-auction costs are certain or the bidder is risk neutral. If all agents have CARA preferences with coefficient $\lambda > 0$, then Eq. (a.13) can be solved for the (CARA) risk averse bid function for environments with post-auction cost uncertainty contained in the text Eq. (11).

The density function for the second order statistic (i.e. the second-lowest cost) for a sample of size n from the uniform distribution on $[c_\ell, c_h]$ is

$$f_{C_2}(c^*) = n(n-1)\frac{c^* - c_\ell}{c_h - c_\ell}\left[1 - \frac{c^* - c_\ell}{c_h - c_\ell}\right]^{n-2}\frac{1}{c_h - c_\ell}. \qquad (a.16)$$

Hence the expected value of the second-lowest cost is

$$\int_{c_\ell}^{c_h} c^* f_{C_2}(c^*)\, dc^* = c_\ell + \frac{2(c_h - c_\ell)}{n+1}. \qquad (a.17)$$

Derivation of the equality in (a.17) involves substitution from (a.16) and repeated integration by parts. To find the expected procurement payment for risk neutral agents in the second-price auction, we substitute the expected value of the second-lowest base cost given by (a.17) into the bid function, (7), and then substitute the result into the contract payment function, (2), using Eqs. (a.10) and (1) to get expected procurement, EP_2^N, contained in text Eq. (12). The expected procurement payment for (CARA) risk averse agents in the second-price auction with post auction cost uncertainty, EP_2^A, is derived from Eqs. (1), (2), (a.10), (11), and (a.17), and is contained in text Eq. (14).

REFERENCES

Cox, J., and Grether, D. (1996). ‘‘The Preference Reversal Phenomenon: Response Mode, Markets, and Incentives,’’ *Econ. Theory* **7,** 381–405.

Cox, J., and Isaac, R. M. (1987). ‘‘Mechanisms for Incentive Regulation: Theory and Experiment,’’ *Rand J. Econ.* **18,** 348–59.

Cox, J., Roberson, B., and Smith, V. (1982a). ‘‘Theory and Behavior of Single-Object Auctions,’’ in *Research in Experimental Economics,* Vol. 2 (V. Smith, Ed.), pp. 1–43. Greenwich, CT: JAI Press.

Cox, J., Smith, V., and Walker, J. (1982b). ‘‘Auction Market Theory of Heterogeneous Bidders,’’ *Econ. Lett.* **9,** 319–25.

Cox, J., Smith, V., and Walker, J. (1988). ‘‘Theory and Individual Behavior of First-Price Auctions,’’ *J. Risk and Uncertainty* **1,** 61–99.

Grether, D. (1992). ‘‘Testing Bayes Rule and the Representativeness Heuristic: Some Experimental Evidence,’’ *J. Econ. Behav. and Organization* **19,** 31–58.

Holt, C. (1979a). ‘‘Uncertainty and the Bidding for Incentive Contracts,’’ *Amer. Econ. Rev.* **69,** 697–705.

Holt, C. (1979b). ''Optimal Contract Incentives,'' in *Bayesian Analysis in Economic Theory and Time Series Analysis—the 1977 Savage Dissertation Award Theses* (A. Zellner and J. B. Kadane, Eds.). Amsterdam: North-Holland.

Holt, C. (1980). ''Competitive Bidding for Contracts under Alternative Auction Procedures,'' *J. Polit. Econ.* **88,** 433–45.

Isaac, R. M., and Walker, J. (1985). ''Information and Conspiracy in Sealed-Bid Auctions,'' *J. Econ. Behav. Organization* **6,** 139–59.

McAfee, R. P., and McMillan, J. (1986). ''Bidding for Contracts: A Principal-Agent Analysis,'' *Rand J. Econ.* **17,** 326–38.

Smith, V. (1976). ''Experimental Economics: Induced Value Theory,'' *Amer. Econ. Rev. Papers and Proceedings,* **66,** 274–79.