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ENVIRONMENTAL ECONOMICS OF MILITARY JET FUEL SPILLS: A CASE STUDY FROM ISRAEL

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ABSTRACT

Petrochemical spills in airports and air force bases often cause environmental damage around the world. This article models the economic aspects of jet fuel spills caused by air force activity. The model was modified to evaluate possible pollution prevention policies using available data from the Hatzor case study in Israel. Results indicate that a market-for-used-fuel policy is more efficient than a policy that regulates polluted fuel disposal.

I. INTRODUCTION

The economic literature has extensively studied the costs associated with off-shore oil spills that cause direct and visible damage to the environment, and has identified policies designed to reduce the damage and help prevent the spills themselves [e.g., 1-3]. Onshore oil spills, which have received less attention, include incidental spills, occurring in the petroleum distribution system, and chronic spills that may be caused by local problems of maintenance of improper procedures in the petroleum industry, airports, and air force bases. Both incidental and chronic oil spills affect the immediate surface soil, the unsaturated zone and, in some cases, groundwater aquifers.

The potential damage from incidental and chronic onshore oil spills may be greater and riskier to human beings than that from off-shore oil spills although it may not be immediately apparent. Oil spills at airports and air force bases, the topic of this article, are frequent events and have been documented in many locations such as Strasburg airport in France [4], many air force bases in the United States [5], and Hatzor and Tel-Nof air force bases in Israel [6, 7]. The common practice in such cases has been to rehabilitate the contaminated soil and

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water, an approach that is very costly to society and is ultimately unsustainable. A system of incentives for pollution prevention and control in air force bases might be more efficient and more economical. This article assesses the effectiveness of a non-structured incentive system for possible jet spill prevention policies applied to the case of Hatzor air force base in Israel.

II. MODEL

The objective of the model presented in this article is to maximize the value of total number of flying hours per a given period of time (1 year) minus private and socially internalized remediation cost, subject to a given budget and input factors concerning pilots, technicians, aircraft, maintenance equipment, and fuel. Assume an independent economic unit (air force base) that produces defense services measured in terms of flying time value. This assumption reflects the approach of a self-managed military unit budget-wise: each flying hour is assigned a dollar value (P) that can be interpreted broadly as the value society attaches to the security produced by each hour of this air force activity. To reduce the potential of pollution from unloaded fuel, regulations or incentives are introduced.

The objective function is

$$Max\,\Pi = \sum_{i \varepsilon I} \; \sum_{j \varepsilon J} A_i X_{ij} P_{ij} - S - H \tag{1}$$

where X_{ij} is flying hours per year, i is aircraft type ($i \in I$), j is sortie type ($j \in J$), and A_i is the number of aircraft of type i, S is the private treatment and storage cost associated with jet fuel to be requiring disposal, and H is the social cost associated with ground water remediation.

Technical training and operational requirements dictate, via an exogenous decision, a ratio (a_{ij}) between sortie types for each aircraft such that

$$a_{ij} \leq \frac{A_i X_{ij}}{\sum_{j \varepsilon J} A_i X_{ij}} \leq a_{i,j+1} \qquad \supset i \varepsilon I;\, j \varepsilon J \tag{2}$$

Other implicit factors, not introduced here, such as the supply of pilots, technicians, and repair equipment, affect the number of flying hours per aircraft. This is expressed by

$$\sum_{j \varepsilon J} X_{ij} \leq b_i \qquad \supset i \varepsilon I, \tag{3}$$

where b_i is a constraint on total annual flying hours for aircraft type i. These boundaries are dictated administratively.

Jet fuel is unloaded and disposed of on several occasions. Some of the unloaded fuel is unsuitable for future use, and therefore might be a source of pollution if not handled properly. This may happen during regular maintenance, which is required after a certain number of flying hours regardless the sortie type, and which results in a disposed quantity of

$$D_m = \sum_{i\varepsilon I} \left(\frac{\sum_{j\varepsilon J} A_i X_{ij}}{c_i} \cdot d_i \right) \tag{4}$$

where c_i is the time gap (flying hours) between maintenance, and d_i is the amount of jet fuel to be disposed per maintenance. c_i is determined by the manufacturer and given exogenously.

Another occasion where jet fuel is unloaded and disposed of is when sorties are canceled. In this case all jet fuel needs to be unloaded from the aircraft. Part of the fuel (a fraction α_i) can be recycled and be re-used immediately. This amount of jet fuel is

$$D_r = \sum_{i\varepsilon I} \left(\alpha_i \cdot \frac{\sum_{j\varepsilon J} A_i X_{ij}}{e_i} \cdot f_i \right), \tag{5}$$

and part, represented by the fraction $(1 - \alpha_i)$, is unsuitable and requires disposal. The amount of jet fuel that must be disposed of due to sortie cancellation is

$$D_c = \sum_{i\varepsilon I} \left((1 - \alpha_i) \cdot \frac{\sum_{j\varepsilon J} A_i X_{ij}}{e_i} \cdot f_i \right), \tag{6}$$

where e_i is time (hours) between malfunctioning and flight cancellations, and f_i is the amount of jet fuel to be unloaded per cancellation event. Therefore, the total amount of unloaded jet fuel that needs to be disposed of ($\overline{D}^w$) is $D_m + D_c$, and the amount that can immediately be re-used is D_r.

$$\overline{D}^w = D_m + D_c \tag{7}$$

With no incentives to prevent pollution, the amount $\overline{D}^w$ is a potential source of pollution of soil and groundwater. To prevent this pollution, standards or taxes on jet fuel spills may be imposed, or, if the jet fuel unsuitable for refueling can be used for other purposes (e.g., for home heating), it can either be sold or exchanged for fresh fuel. The air force base can exchange an amount D^w against new jet fuel for an exchange rate of β units ($\beta < 1$).

$$D^w \leq \overline{D}^w. \tag{8}$$

In the case where fuel is traded, the amount of available jet fuel in addition to the original budgeted amount is

$$D = D_r + \beta \cdot (D^w). \tag{9}$$

The total annual budgeted quantity of jet fuel per aircraft (M_i) plus the additional amount allocated to aircraft type i can be used to generate flying hours. The jet fuel constraint is therefore

$$\sum_{i\epsilon I}\sum_{j\epsilon J} A_i X_{ij} \cdot g_{ij} \leq \sum_{i\epsilon I} A_i \cdot (\gamma_i \cdot D + M_i) \tag{10}$$

where g_{ij} is jet fuel consumed per hour of sortie j by aircraft i. γ_i is the share of recycled jet fuel allocated to aircraft i. M_i and γ_i are determined administratively and exogenously to the system.

The amount D^w of jet fuel that is exchanged needs to be stored until disposed of or traded. Storage (C) for the unsuitable jet fuel is limited,

$$D^w \leq C \tag{11}$$

and the cost associated with treatment and storage of D^w is

$$S = s\,(D^w). \tag{12}$$

The function s increases in D^w. If S is too high, or if there are no incentives for recycling the unloaded jet fuel, then $\overline{D}^w > D^w$ and the amount of jet fuel disposed to the aquifer is $\overline{D}^w - D^w$. The social cost associated with its remediation is a non-decreasing function of $\overline{D}^{w} - D^w$.

$$H = h(\overline{D}^w - D^w). \tag{13}$$

It is clear that if S = 0, then in the optimal solution $D^w = \overline{D}^w$ and $H = 0$. In the case where the air force base is faced with quotas on budgeted jet fuel for its activity or constraints on disposed jet fuel, then the model may suggest reduction in the annual number of flying hours. To provide a minimal level of security (defense), it is assumed that there is a lower limit ($\overline{X}$) on flying hours per year with which the solution of the model must comply

$$\sum_{i\epsilon I}\sum_{j\epsilon J} A_i X_{ij} \geq \overline{X}. \tag{14}$$

The problem of maximizing (1) subject to constraint (2)-(14) is clearly a problem for which Kuhn-Tucker (KT) analysis may offer a solution. The KT conditions can explain the relationships between variables included in the optimal solution. Each constraint Q_m of the problem is assigned a shadow price δ_m where m is the m'th constraint as enumerated in the model equations. The KT conditions require that for each variable $x_i \geq 0$ in the optimal solution:

$$\frac{\partial \Pi}{\partial x_i} - \sum_m \delta_m \frac{\partial Q_m}{\partial x_i} = 0.$$

The KT analysis is conducted for the decision variables X_{ij} and D^w only, although additional variables might have been included as well. The results suggest two relationships. The first relationship is:

$$\frac{\partial D^w}{\partial X_{ij}} = \frac{\delta_3 + A_i \cdot \Theta}{\delta_9 \cdot \beta}$$

where

$$\Theta = \left\{ P_{ij} - \left(\delta_2 - \delta_2' \cdot \frac{\sum\limits_{j\varepsilon J} A_i X_{ij} - A_i X_{ij}}{\left(\sum\limits_{j\varepsilon J} A_i X_{ij} \right)^2} + \frac{d_i}{c_i}(\alpha_3 + \alpha_4) \right) + \frac{f_i}{e_i}[\alpha_i(\delta_5 - \delta_6 - \delta_7 + \delta_9 + \delta_{10})] - \delta_{10} g_{ij} - \delta_{14} \right\}.$$

The first equality above means that in the optimal solution the marginal value of fuel $\left(\frac{\partial D^w}{\partial X_{ij}}\right)$ should equal the marginal value of an additional flying hour $\frac{\delta_3 + A_i \cdot \Theta}{\delta_9 \cdot \beta}$. The variables in the latter expression are: the shadow price of other constraints on flying hours (δ_3), the shadow price of fuel storage (δ_9), and Θ is the alternative value of increasing the flying constraint by an additional flying hour. This variable can be interpreted as the difference between the social value of national security associated with an additional flying hour and the social (environmental) cost associated with this additional flying hour.

The second relationship is:

$$\frac{\partial s}{\partial D^w} + \frac{\partial h}{\partial D^w} = \delta_{10} \sum_i \beta A_i \gamma_i + \beta \delta_3 + \delta_8 - \delta_{11}$$

which means that in the optimal solution the sum of marginal storage and treatment cost of the jet fuel spilled and the social cost associated with the pollution by the disposed fuel should equal the sum of the alternative costs associated with increasing fuel quantity available for additional flying hours.

III. RESULTS FROM THE HATZOR CASE STUDY

The model was applied to the Hatzor base in Israel. Jet fuel has been detected in the drinking water supply of several municipalities near the Hatzor air force base in 1983 [6]. It was found that improper refueling and fuel unloading procedures over twenty years in the air force have caused spills of approximately 20,000 m^3 of jet fuel that percolated deeply into the unsaturated zone and also contaminated the aquifer water.

It is assumed that the air force maximizes the net social returns from its activity. On the request of the IDF the empirical model was modified to a simplified case with two aircraft types and two sortie types per aircraft. The analysis was performed in terms of flying hours per year per aircraft (with no explicit number of aircrafts). Therefore, all coefficients were normalized to that level. In addition, several explicit factors, such as manpower, equipment, and other technical constraints have been transformed into specific coefficients in the optimization problem. All air force flying hour data were provided by IDF, based on operational files from Hatzor air force base. Treatment and aquifer recovery cost functions were estimated based on [8].

The model for the case of $i = j = 2$ is:

$$\sum_{i=1}^{2}\sum_{j=1}^{2} X_{ij}P_{ij} - H - S. \tag{15}$$

The literature does not provide estimates for Pij. Therefore, the budgeted hourly cost can be used as a conservative estimate. Values provided by IDF suggest \$13,000 and \$11,500 per hour for air craft type 1 and 2, respectively. No distinction is made between sortie types. However, it is recognized that differences exist for each aircraft type; accordingly, the following ratio was determined. The ratio between sortie types is

$$a_{11} \le \frac{X_{11}}{X_{11} + X_{12}} \le a_{12} \tag{16}$$

for aircraft type 1, and

$$a_{21} \le \frac{X_{21}}{X_{21} + X_{22}} \le a_{22} \tag{17}$$

for aircraft type 2. The ranges were estimated based on logs provided by the base logistics department to be $a_{11} = 0.55$, $a_{12} = 0.7$, $a_{21} = 0.4$, and $a_{22} = 0.6$.

The annual number of flying hours is bounded:

$$X_{11} + X_{12} \le b_1 \tag{18}$$

$$X_{21} + X_{22} \le b_2. \tag{19}$$

The value of b_i is implicitly affected by the level of constraints such as manpower, equipment, etc. as was explained earlier and is set at the level of $b_1 = 80$ and $b_2 = 70$ hours.

Unloaded fuel during maintenance is

$$D_m = \left(\frac{X_{11} + X_{12}}{c_1} \cdot d_1 + \frac{X_{21} + X_{22}}{c_2} \cdot d_2 \right) \cdot \Psi \tag{20}$$

where $c1 = c_2 = 50$ hours is provided by the manufacturer, and d_1 and d_2 are both characterized with a mean of 2250 Lb and 1000 Lb, respectively. The range of their values is 1500-3000 Lbs. and 500-1500 Lbs., respectively.[1] Since the analysis here is in terms of flying hours per aircraft, then, in order to get the real amount of unloaded jet fuel, one needs to use the actual ratio ψ between the number of aircraft type 1 and 2, which is 3/2.

In a similar way, the amount of fuel unloaded after sortie cancellations and re-used immediately is

$$D_r = \left(\alpha_1 \cdot \frac{X_{11} + X_{12}}{e_1} \cdot f_1 + \alpha_2 \cdot \frac{X_{21} + X_{22}}{e_2} \cdot f_2 \right) \cdot \Psi \tag{21}$$

and the amount unloaded that is unsuitable and needs disposal is

$$D_c = \left((1 - \alpha_1) \cdot \frac{X_{11} + X_{12}}{e_1} \cdot f_1 + (1 - \alpha_2) \cdot \frac{X_{21} + X_{22}}{e_2} \cdot f_2 \right) \cdot \Psi \tag{22}$$

where e_1 and e_2 have means of thirty hours and twenty hours, respectively (no range of values was provided). The parameters f_1 and f_2 are associated with means of 7500 Lbs. and 4000 Lbs., respectively. Their values range between 4,000-10,000 Lbs. and 1,000-5,000 Lbs., respectively. α_1 and α_2 are associated with means of 0.9 and 0.8, respectively (no range of values is provided).

In addition the balance equations are used as in the general model

$$\overline{D}^w = D_m + D_c \tag{23}$$

$$D^w \leq \overline{D}^w. \tag{24}$$

In the case study analyzed here the unloaded fuel during maintenance is drained into small operational containers and then removed periodically to a central container of unsuitable fuel. The volume of fuel that can be stored in this system is very limited. Unloaded fuel during flight cancellations is pumped first to a drain container. Of this amount a share of α_1 and α_2 for aircraft type 1 and 2, respectively is reused immediately, and the remainder $(1-\alpha_1)$ and $(1-\alpha_2)$ is pumped to the central container of unsuitable fuel. This fuel is sold to the company which exchanges a fraction β of usable fuel against each Lb. of unsuitable fuel (β = 0.3-0.5 Lbs.). (The range in values reflects summer and winter demands.) The total amount of fuel available for use is therefore

$$D = \{D_r + \beta \cdot (D^w)\} \cdot \Psi. \tag{25}$$

Under the conditions prevailing in the air force base in this case study, the storage and transportation cost associated with disposing of the unsuitable fuel is

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[1] All fuel data was recorded from the fuel monitoring unit books at the Hatzor air force base. The presentation or use of distribution coefficients for the fuel spill variables ($d_{.i}$, e_i, f_i, α_i) were not allowed by the IDF censorship. Therefore, mean values and ranges (where available) for the relevant variables will be used.

a one time investment with a very long time span which results in almost a negligible cost. Therefore, $S = 0$, and the model will suggest the treatment of all disposed fuel. However, the empirical illustration assumes a cost of \$0.3 per Lb. of unsuitable fuel that includes both construction, manpower, and transportation costs.

The storage capacity for the unsuitable fuel is allocated administratively to the two aircraft types

$$\frac{X_{11} + X_{12}}{c_1} \cdot d_1 + (1 - \alpha_1) \cdot \frac{X_{11} + X_{12}}{e_1} \cdot f_1 \leq C_1 \tag{26}$$

$$\frac{X_{21} + X_{22}}{c_2} \cdot d_2 + (1 - \alpha_2) \cdot \frac{X_{21} + X_{22}}{e_2} \cdot f_2 \leq C_2 \tag{27}$$

for aircraft type 1, and 2, respectively. The values for C_1 and C_2 were the same at the level of 8,400 Lbs./yr./aircraft. In the analysis, C_i were also considered as decision variables and their values were internally determined.

The additional fuel can be allocated to the different aircraft types so that the objective function is maximized. The fuel allocation relationships for the two aircraft types are

$$X_{11} \cdot g_{11} + X_{12} \cdot g_{12} \leq M_1 + \gamma 1 \cdot \mathrm{D} \tag{28}$$

$$X_{21} \cdot g_{21} + X_{22} \cdot g_{22} \leq M_2 + \gamma_2 \cdot \mathrm{D}. \tag{29}$$

In the empirical model the additional fuel is administratively allocated among the aircraft types such that $\gamma_1 = \gamma_2 = 0.5$. The original fuel allocation (M_i) to each aircraft type is 920,000 Lbs. and 500,000 Lbs. per year per aircraft, respectively. Fuel consumption per flying hour by sortie type and aircraft type is taken from the manufacturer manual. Values are $g_{11} = 13{,}200$, $g_{12} = 8{,}000$, $g_{21} = 9{,}200$, and $g_{22} = 7{,}000$ Lbs. per hour per year.

The model was run to simulate several scenarios. A non-regulated base run does not include the pollution cost components in the objective function; these costs are calculated separately and subtracted from the objective function value. A second run allows a full recycling of the fuel with no recycling cost. And a third run is identical to the second one but includes the pollution costs as constraints.

Treatment and Recovery Cost Function of the Contaminated Aquifer

Several available technologies are analyzed in [8] for their cost-effectiveness in achieving a certain reduction in fuel-contaminated groundwater aquifer. Each technology can be used individually or with other technologies. A similar approach has been used by Noonan and Curtis [9]. We chose to use a subset of four technologies that have been analyzed in [8], and estimated an envelope

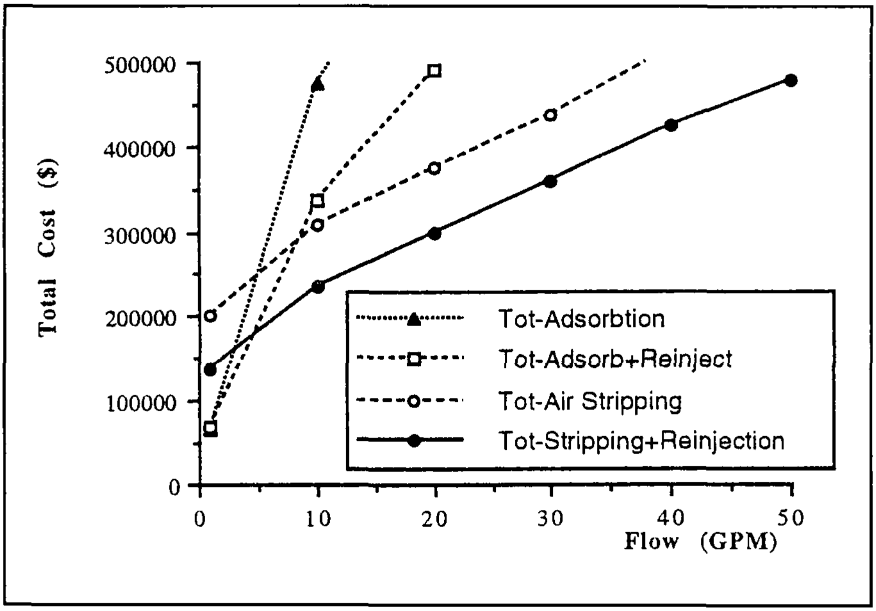

Figure 1. Total clean-up cost of fuel-contaminated aquifers using four treatment technologies.

treatment cost function. The technologies evaluated are activated carbon adsorption, air stripping, carbon adsorption+reinjection, and air stripping+reinjection. For a technical description of the technologies and their cost data, the reader is referred to [8] and [10].

The total cost curves for the four technologies were calculated and plotted in Figure 1 against the flow of fuel from the aquifer.[2] Then, the envelope curve was plotted and a quadratic envelope cost function was estimated (see Figure 2). In order to prevent the polluter from being in the decreasing zone of this cost function by increasing pollution, a monotonic increasing cost function was fitted to the data in Figure 2. In order to fit the cost function to the data available in the Hatzor case study, the flow units were changed to volume (or weight) unites of spilled fuel.

[2] Kanfi [11] provided a range of cost estimates based on cleanup bids submitted by several companies for the Or A'kiva jet fuel spill in Israel. In this event about 377 m^3 of jet fuel have been spilled contaminating 70,000 m^3 of soil. No further information is provided for the amount of groundwater affected. Clean-up cost estimates for this site range between $1.7-2.1 million. Using the conversion factor of 1 liter of jet fuel = 0.8805735 Lbs., the average clean-up cost per 1 Lb. spilled equals $6.32 in 1993 values. Cohen [2] estimated the cost of oil spill prevention by the US Coast Guard at $5.50 per Gallon in 1981 values.

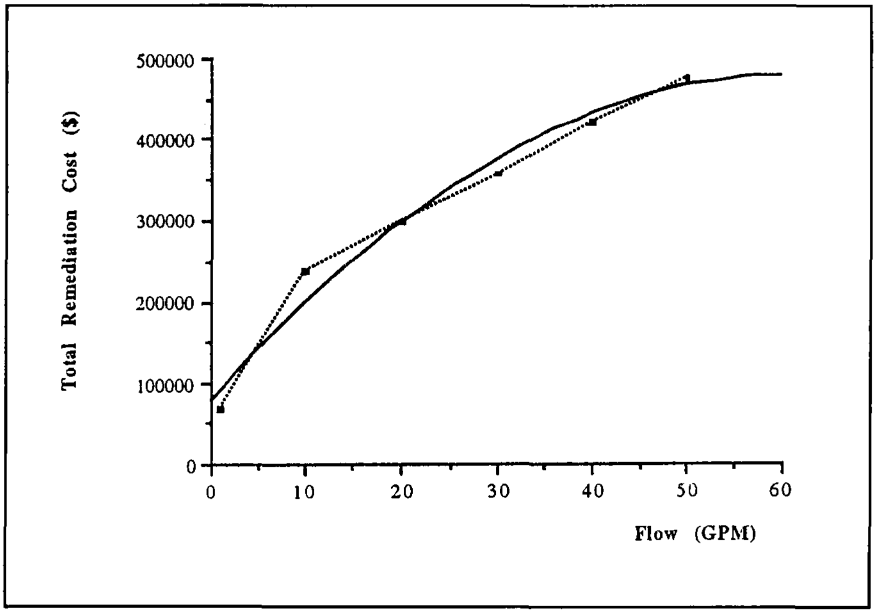

Figure 2. A total clean-up envelope cost function of fuel-contaminated aquifers.

Specific remediation cost estimates for the Hatzor Case study were prepared by suing an exponential version of the envelope curve in Figure 2. The data in Figure 2 were adjusted to 1991 dollar values using the consumer price index in [12], and units were modified from flow—gallons per minute (GPM) to weight (Lbs). (1 Liter of jet fuel = 0.8805735 lbs.) Only the range 0-20 GPM, that represent the Hatzor case, was used. The simplified curve for remediation costs of the form $H = 50 \cdot (\bar{D}^w - D^w)^{.950}$ is applied in the illustration of the two aircraft.

Several scenarios were simulated. The first is a non-regulated base case that does not include the pollution remediation cost component in the objective function. This cost is calculated separately and subtracted from the objective function value. In this case no storage is considered and the market for re-used fuel is not viable. Other simulations include the current situation where the storage is limited to a small operational capacity, and exchange of unsuitable jet fuel in the market is not possible. Several storage capacity constraint levels were examined and compared. Then, the trade option was considered but the storage constraint was still in effect. Several constraint levels were compared. The results of those analyses are presented in Table 1. Finally, the model allowed storage to be treated as an endogenous decision variable, and it allowed the market for unsuitable fuel to be a viable option. Several sensitivity analyses were performed to account for

Table 1. Effects of Storage Capacity and Market for Unsuitable Fuel on Flights and Pollution

Scenarios	Base	1	2	3	4	5	6
Market exchange rate	0.0	0.0	0.0	0.0	0.4	0.4	0.4
Storage (Lb./Aircraft)	0.0	850.0	2,500.0	5,000.0	850.0	5,000.0	N/A
Fuel stored (Lb.)	0.0	1,133.4	3,333.3	6,666.6	1,133.4	6,666.6	9,956.1
Aircraft type 1 (hours)							
Sortie type 1	30.0	2.2	6.5	21.1	2.2	20.9	44.0
Sortie type 2	40.0	1.8	5.3	17.3	1.8	17.2	36.0
Aircraft type 2 (hours)							
Sortie type 1	25.0	5.6	16.6	26.4	5.6	26.6	27.2
Sortie type 2	45.0	8.5	25.0	39.7	8.5	39.9	40.8
Fuel consumed (Lb.)	1,403,724	155,600	457,616	939,708	155,600	939,166	1,405,666
Fuel unloaded (Lb.)	7,022	1,001	2,946	5,415	1,001	5,426	7,087
Unloaded/Consumed	.006542	.006433	.006437	.005762	.006433	.005777	.005041
Fuel polluting (Lb.)	80.7	57.3	4.2	0.0	57.3	0.0	0.0
Social net benefit ($)	79,441	145,871	429,014	848,972	145,871	849,172	1,218,872
Shadow price of storage ($)							
Aircraft type 1	N/A	0.0	8.8	172.0	0.0	0.0	N/A
Aircraft type 2	N/A	8.8	0.0	0.0	8.8	0.0	N/A

Note: N/A = Not applicable.

the observed range of values of some of the parameters; the results of these analyses are presented in Table 2.

The results of the base run suggest that the air force produces a substantial number of flying hours at the lowest value of social benefit compared to all other scenarios. Since remediation costs were not included in the objective function of the air force, the externality associated with the operation was not considered. Society, however, pays for remediation, and therefore, the resulting social net benefit is the lowest ($79,441). All monetary values in the analysis are expressed in real May 1993 U.S. dollars.

Three values of storage constraints were considered in scenarios where the market for unsuitable fuel was not available. They are numbered as scenarios 1-3 in Table 1. In the case of a very effective storage capacity (850 lb.) for used fuel (scenario 1), the resulting flight hours of the two aircraft types are the lowest (18.6 hours), the amount of fuel disposed is the largest (57.3 lb.), and the social net benefit is the lowest ($145,871) among the three scenarios covering no market and effective storage for unloaded fuel. As fuel storage capacity grows from 850 to 2,500 Lbs. per year, the air force activity grows to 53.4 hours, the amount of fuel disposed decreases to 4.2 lb., and the social net benefit increases to $429,014. The highest storage capacity that was considered in the analysis, 5000 Lb., allowed the highest number of flying hours (104.5 hours). No fuel was disposed of to the environment. This scenario gave the highest net benefit of all scenarios ($848,942).

Scenarios 4-6 introduce the market for used fuel with a given exchange rate of 0.4 units of fresh jet fuel for each unit of traded disposed fuel. For storage constraints of up to 5,000 Lb., the results for the "with market" scenario are very similar to the "without market" scenario. The reason is that the storage capacity is an effective constraint that eliminates all potential benefits from exchange of used for fresh jet fuel. When the storage constraint is removed (scenario 6), air force activity is maximized (150 hours) and, disposed fuel is still kept at 0 lb. The social net benefit in that case is the highest, $1,218,872—about 40 percent higher than with 5,000 lb. of storage capacity.

The observed coefficients of the air force production process vary within a given range. Table 2 presents the results of a sensitivity analysis associated with some of these coefficients. The three coefficients—d_i, f_i, and β—representing fuel unloaded due to maintenance, sortie cancellation, and market exchange rate, respectively, were included in the sensitivity analysis. The reference run was the one represented by scenario 6 in Table 1. Values for these coefficients that are lower and higher than the values used in the base run were used to account for the possible range of values associated with a given observed range of these coefficients.

The results in Table 2 suggest that the optimal solution is not sensitive to the variation in these coefficients, once the market option is provided and where storage capacity is unlimited. The number of flying hours for the two aircraft

Table 2. Sensitivity Runs for State Variables at Market Option and No Storage Limit

		Fuel Unloaded (Maintenance)		Fuel Unloaded (Sortie Cancelation)		Market Exchange Rate for Unsuitable Fuel	
	Reference[a]	Low	High	Low	High	Low	High
Stored fuel (Lb.)	9,956.1	1,170.5	17,365.3	9,950.9	16,697.2	14,518.9	14,544.5
Aircraft type 1 (hours)							
Sortie type 1	44.0	44.0	44.0	44.0	44.0	44.0	44.0
Sortie type 2	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Aircraft type 2 (hours)							
Sortie type 1	27.2	27.2	27.3	26.2	27.8	27.1	27.3
Sortie type 2	40.8	40.8	40.9	39.3	41.7	40.7	41.0
Fuel consumed (Lb.)	1,405,666	1,404,800	1,406,541	1,385,533	1,416,441	1,404,550	1,406,791
Fuel unloaded (Lb.)	7,087	7,081	7,094	2,583	9,212	7,079	7,096
Unloaded/Consumed	.005041	.005040	.005043	.00186	.00650	.005040	.005044
Social net benefit ($)	1,218,872	1,302,614	1,135,031	1,329,328	1,168,336	1,217,758	1,219,989

[a] Scenario 6 from Table 1.

types was almost identical for each of the runs. The storage capacity was adjusted in the different runs to the unloaded fuel, and the social net benefit reflected the air force investment cost in storage. Clearly, in none of these solutions does any fuel contaminate the aquifer.

The model was also used to compare pollution regulations with the institutional arrangement that allows exchange of unsuitable fuel. The comparison was performed by limiting the amount of polluting fuel (assuming no monitoring cost) while allowing investment in storage and eliminating the exchange arrangement. The benchmark run was scenario 4 in Table 1 (but without the market option). The results (Figure 3) demonstrate the lower efficiency of the regulatory measures, compared with the market option. In all cases, the net social benefits is lower.

CONCLUSION

Pollution of soil and ground water by jet fuel spills during air force activity has become a major environmental problem. In many cases the fuel leaks and accumulates in the soil and in aquifers until a major crises occurs. At that time drinking water sources are contaminated, human health is placed at risk, and millions of dollars need to be spent in clean-up costs.

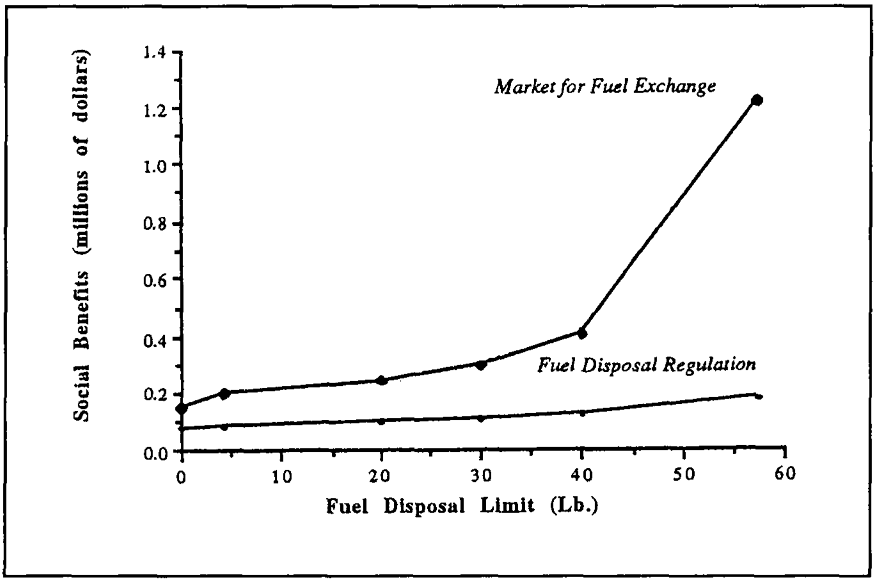

Figure 3. Comparison of social benefits resulting from regulation and market for fuel.

In this article we developed a production-pollution model that describes air force activity and the major decision-making functions that are related to the air force activity on the one hand and to the potential jet fuel spills associated with this activity on the other hand. We examined several approaches to managing jet fuel pollution.

If the air force base is managed as a dependent unit, then no incentive exists to prevent pollution, either by investing in storage, by decreasing flight numbers, or by changing flight mixes. Establishing a market for the unloaded jet fuel that may otherwise become an environmental threat may reduce the pollution by providing incentives for storage and exchange of used fuel for fresh fuel. If the air force base storage capacity of unloaded fuel is limited, however, then there still might be some non-negligible level of pollution. When the storage capacity is unlimited, even if it is financed by the air force, pollution is minimized, and in the case analyzed here, eliminated. Serial benefits were calculated here as the assigned values of air force flying hours net of fuel cost, "private" storage, and social clean-up costs. The values of social net benefits are substantially higher in the case of an unlimited storage capacity and market for fuel, compared with all other scenarios.

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