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EVOLUTIONARY DEVELOPMENT of a SIMULATION MODEL USED for POLICY PLANNING and DEVELOPMENT

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ABSTRACT

The Strategic Petroleum Reserve Distribution (SPRED) Model is a large-scale discrete event simulation model developed for the U.S. Department of Energy (DOE), Strategic Petroleum Reserve (SPR). It was originally developed jointly for the U.S. Maritime Administration and the Federal Energy Administration in 1978. It models the petroleum marine distribution network, the operation of specific SPR petroleum terminals, and selected U.S. receiving terminals. It determines the capabilities of the marine distribution system to deliver SPR petroleum. It has undergone substantial evolutionary change over the last four years and has been used to support DOE policy analysis and development. It is a good example of a planning tool which was developed in a responsive, evolutionary manner in close cooperation with agency users to become a successful public policy evaluation and development tool.

1. INTRODUCTION

The Strategic Petroleum Reserve Office (SPR) of the U.S. Department of Energy (DOE) has been tasked with developing and implementing programs for the creation and management of a Strategic Petroleum Reserve to be used by the U.S. in the event of a crude oil supply interruption or an international energy emergency. This reserve was authorized by Congress with the passage of the Energy Policy and Conservation Act (P.L. 94-163), which was approved December 22, 1975, and extended in July of 1985. This legislation declared it to be United States policy to establish a Strategic Petroleum Reserve of up to one billion barrels of petroleum to reduce the impacts of disruptions and to carry out the obligations of the United States under the International Energy Program.

The development of this petroleum reserve is presently over two-thirds completed and systems for the ultimate emergency distribution and use of reserve crude oil are continually being enhanced. A substantial portion of the reserve petroleum will be distributed via waterborne carriers from the SPR petroleum terminals along the Gulf coast to a large number of U.S. ports which currently receive crude oil shipments. The primary objective of the Strategic Petroleum Reserve Distribution (SPRED) simulation model is to provide SPR with a practical management tool to be used to assist DOE in planning, evaluating, and implementing SPR policy regarding emergency reserve distribution. The model provides a rigorous and flexible way of methodically evaluating the capabilities of an available maritime fleet to move SPR oil, determining workable SPR distribution strategies given distribution goals and available resources, and developing the maritime distribution forecasting data necessary for SPR management decision making.

2. WHAT SPRED SIMULATES

The SPRED model is a set of computer programs which simulate certain key activities associated with the physical movement of ships, the operation of petroleum terminals, and the loading and unloading of ships. Information provided to the SPRED programs as input data enables a user to define a given distribution system -- a group of SPR terminals and receiving terminals with specific physical operating characteristics that describe their capabilities. The SPRED model recreates the operation of this system with a given fleet of ships, providing a way to evaluate its overall performance given a variety of dynamic operating conditions.

The model simulates two types of activity. The normal arrival of petroleum at the receiving terminals located at U.S. ports, called business-as-usual (BAU) operations, is replicated using historical delivery data. The distribution of reserve petroleum during energy emergency supply interruption conditions is simulated first, by reducing the BAU petroleum arriving at U.S. ports, and second, by starting the distribution of reserve petroleum from the SPR terminals to selected receiving ports given a dedicated fleet of tankers available for SPR distribution. The activities described below are illustrated schematically in Figure I.

2.1. Business-as-Usual Activities

BAU operations represent the normal everyday levels of petroleum shipping activity at ports with petroleum terminal facilities. Recent historical data describing throughput statistics and ship arrival profiles are used by the model to build representative ship arrival schedules at the receiving terminals (petroleum terminals at U.S. ports which receive imported or domestic crude oil). These statistically generated ship arrivals, together with a description of key terminal characteristics which determine terminal operation (e.g., tankage, docks, pumping rates), provide the information needed to simulate receiving terminal operations over a long period of time.

The BAU ships which arrive at the receiving terminals are "statistical" ships which are created (based upon a given terminal's ship arrival profile), move through the terminal and unload, leave the terminal and "disappear". Their purpose is to provide realistic levels of shipping activity at the terminals. The following activities are replicated at the receiving terminals under BAU conditions:

* A BAU tanker is "created" in the model based on data supplied to the model in the data base
* The tanker "arrives" at the destination port sea buoy
* The tanker proceeds from the sea buoy to a terminal anchorage area
* As soon as a dock is available, the ship proceeds to the receiving terminal to unload its cargo
* As the ship unloads, the petroleum is pumped into storage tanks and stored temporarily
* After unloading, the ship moves out of the dock, and leaves the terminal
* The BAU ship next "exits" from the port and leaves the distribution system
* As ships arrive, unload, and leave, the oil is pumped out of the storage tanks at specified rates to another non-specific destination

The model does not simulate the movement of BAU petroleum prior to arrival at its destination port or subsequent to leaving the storage tanks at the receiving terminals. Each BAU ship makes only one appearance in the system; it arrives, delivers its load of petroleum, and leaves.

2.2. Supply Interruption Activities

Supply Interruption operation represents energy emergency conditions under which normal petroleum shipping activities at receiving terminals would be partially or totally curtailed. This curtailment creates a shortfall in the normal amounts of petroleum needed at affected terminals and refineries. The SPRED model replicates the distribution of SPR petroleum to partially offset this loss given a set of receiving terminal shortfall replacement goals. This is done using a dedicated fleet of ships only used to distribute crude oil from SPR terminals (terminals linked to the SPR reserve petroleum storage sites) to receiving terminals. A description of the key characteristics which determine SPR terminal operation (e.g., tankage, inflow rates, batching cycles, pumping rates) provides the information needed to simulate SPR terminal operations.

The SPR ships which transport reserve crude oil are dedicated to reserve distribution and never "leave" the distribution system. They wait in an SPR ship pooling area until dispatched to an SPR terminal, move through the SPR terminal and load, travel to a selected receiving terminal, unload, leave the receiving terminal, and travel back to the SPR ship pool. At the pooling area, they wait until selected and sent to another SPR terminal. The following activities are replicated under supply interruption conditions:

* BAU operations at the receiving terminals continue as described previously, reduced relative to the amount of shortfall experienced.
* An SPR ship is selected from the available ship pool to be dispatched to an SPR terminal
* The ship leaves the ship pool, travels to the SPR port sea buoy, and proceeds to the terminal anchorage
* As soon as a dock is available, the ship leaves the anchorage, docks, and begins loading
* When loading is complete, a destination receiving terminal is selected and the SPR ship is dispatched from the SPR terminal
* The SPR ship travels to the selected receiving terminal
* The SPR ship arrives at the receiving terminal port sea buoy and proceeds to unload, as described under BAU activities above.
* After unloading, the ship moves out of the dock, leaves the port, and makes the return trip to the SPR ship pool, where it waits to once again be dispatched to a SPR terminal

The model does not replicate the movement of SPR petroleum prior to its flow into the SPR terminal surge storage tanks.

3. BASIC MODEL STRUCTURE

The SPRED model is comprised of five primary programs written in Simscript II.5 as well as a number of IBM TSO command language utility programs which link the operation of the primary programs. These programs comprise a "black box" modeling system which is transparent to the user. In

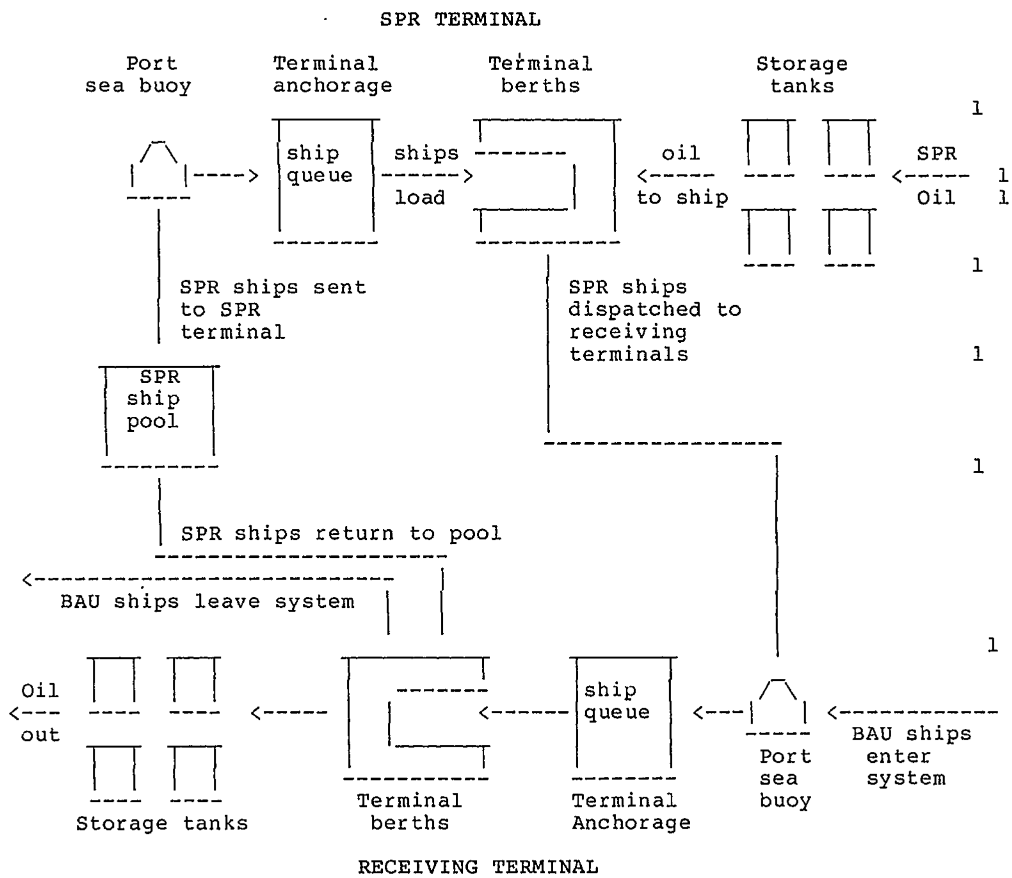

Figure 1: Spred Model Distribution System Configuration

addition, there are four input data files loaded by the model. The model is installed on the Energy Information Administration (EIA) IBM 3083 computer system used by DOE.

The primary model programs are:

- Facility Processor - the facility data processor program which reads the facility data file, provides error checks on file contents, and formats the data for model execution.
- Ship Processor - the ship data processor program which reads the ship characteristics data file and the SPR available ship pool data file, provides error checks on file contents, and formats the data for model execution.
- Event Processor - the event processor program which reads the external event data file, provides error checks on file contents, and reformats the event data for model execution.
- Model Logic Program - the model logic program contains the computerized representation of the distribution system activities being simulated.
- Report Generator - An interactive program which provides facility and ship summary output reports and selective retrieval of specific detail reports expanding upon summary report line items.

A data base of initial facility attribute values, ship fleet characteristic data, available SPR ship pool, and external event scheduling data must be developed and defined to be able to use SPRED in a meaningful way. These data files are:

- Facility data file - This data file contains the port, receiving terminal, and reserve terminal data that is required by the model to define the components of the distribution system.
- Ship characteristic data file - This data file contains the values describing the BAU and SPR ship fleets.
- SPR Available Ship Pool - This data file contains a summary of the number and type of ships available to distribute SPR petroleum.
- Event Data File - This data file contains a chronological list of the external events being scheduled to occur during the course of model logic program execution.

Taken together, these data files define the distribution system being simulated and operational and policy assumptions being examined. The model data describes four system entities:

- Ports
- Receiving terminals
- SPR terminals
- Ships

These entities have more than 100 entity attributes which describe the particular characteristics of each entity and serve as user defined inputs to the model in the data files described above.

4. EVOLUTION OF MODEL DEVELOPMENT

The SPRED model was originally developed jointly for the U.S. Maritime Administration and the Federal Energy Administration in 1978. The model was initially designed and developed under the sponsorship of individuals with completely different policy concerns than those using it now. The original developers were most interested in examining the ability of waterborne SPR crude to make up for lost imports, considering the source and severity of the supply cutoff and the continuing import and domestic traffic at the receiving terminals. Applications of the model subsequent to its initial implementation included analysis of facility requirements at the SPR petroleum terminals and the evaluation of the potential SPR drawdown capacities required given specific supply interruption (embargo) scenarios from OPEC countries.

More recently policy concerns have moved away from the replacement issue. Model evolution and application have moved away from overall throughput concerns to a more specific question - an assessment of the marine resources needed to support specified SPR drawdown rates and distribution patterns. It is probable that marine vessels will be required to move crude oil in unprecedented quantities on both normal and atypical domestic coastwise shipping routes. By using SPRED in conjunction with other crude oil supply and demand data available within DOE, it is possible to develop supportable estimates of the resulting quantities and destinations of SPR crude oil coming out of the Gulf ports.

4.1. Original Model Design

The original version of the model worked on a demand driven basis in that the user defined normal "business-as-usual" oil inflow levels at a large number of U.S. ports, providing a substantial amount of background data such as crude type amounts, country of origin, and type of carrier. The user would then describe a supply interruption to the model along with a description of the SPR facilities and operating constraints. The model would then simulate the operation (drawdown) of the reserve to most efficiently attempt to replace the interrupted oil inflows at the U.S. ports affected. This was a useful approach since it helped answer two of the key questions which arose during the intial SPR development phases: first, how effectively could SPR realistically expect to respond to interruption emergencies, and second, what levels of shipping activity would be required at the SPR petroleum terminals to sustain SPR distribution for extended periods of time (and what operational problems and policy concerns are likely to be encountered in doing so).

4.2. Model Revisions and Updates

As SPR construction and fill continued and evolved, emphasis was added to more detailed drawdown and distribution planning. Foremost among the distribution concerns was the adequacy of the maritime fleet that might be available to distribute the reserve oil. The adequacy of the Jones Act fleet (the fleet of U.S. flag ships given exclusive right by law to carry domestic coastwise commodity movements) had always been uncertain and now became a concrete issue. SPRED was a logical tool to use in analyzing this issue since it modeled the environment and operations in which Jones Act vessel sufficiency would be tested and allowed critical elements such as the number and physical characteristics of available U.S. flag ships to be user controlled input variables. The SPR physical system had matured, however, and general policies had evolved regarding SPR distribution which made many of the underlying model logical assumptions unrealistic or obsolete.

The model first underwent a general logical redesign which changed it from a demand driven basis to a supply driven basis. Rather than attempting to compute the most efficient drawdown of the SPR oil to meet the given supply shortfalls, the model was substantially revised to distribute SPR oil from the SPR terminals to the receiving terminals on a supply driven basis, filling available ships as fast as the terminal facilities and the dedicated ship fleet allow. The user provides the model various data describing the crude type drawdown patterns (cycles) and amounts at the SPR terminals, SPR terminal facilities, and terminal operating constraints. In addition, petroleum terminal operating logic was revised to make representation of the SPR terminals more realistic, more user controlled logical options were incorporated into the model programs, new output reports were added, and the user friendliness of the model was improved.

The updated model was used for a series of analyses assessing the impact of the Jones Act upon the fleet of ships likely to be available to distribute SPR oil during an emergency. As clarification of the facts and factors pertinent to the Jones Act question evolved, the model underwent a series of expansions, refining input data describing the ship fleet, revising operating logic of the SPR petroleum terminals, and substantially expanding the model output statistics describing the movement and utilization of the ship fleet. As analyses of specific fleet utilization questions were performed, the Jones Act issues themselves were clarified.

No model should be used beyond the scope for which it was designed. However, by studying problems not necessarily envisioned when the model was designed, but still within the general scope of its capabilities, useful refinements in both the model and decisions based upon model results can evolve. This happened all along the Jones Act fleet evaluation route. As one example, the case of barges is illustrative. By including barges, which have relatively small oil carrying capacities, in the available ship pool it was found that the terminals became disproportionately congested with barge traffic. This happened because barges represented a large proportion of the gross number of vessels in the ship pool but a much smaller portion of total carrying capacity. This led to logical changes in the way vessels were selected from the available pool, the way vessels were assigned to berths at the terminals, and the controls the user can impose on ship selection and terminal berth availability.

DOE planners have actively refined SPRED and view it as an evolving tool fundamental to the SPR drawdown and distribution planning process. For these purposes, SPRED has already been used in conjunction with other models representing other aspects of the overall SPR facilities assessment and design and operations planning processes. In addition to being useful for planning purposes, it is the objective of DOE to have SPRED accepted as the government's definitive methodology for assessing the Jones Act requirements at the time of an energy emergency and reserve distribution.

The keys to the successful development and application of the SPRED model are twofold. First, the model was developed in close and responsive cooperation with agency users. At no one point was it considered "final" or were the technical and operational specifications inflexibly imposed. Secondly, both the model developers and agency personnel used results from applications of the model to closely examine how the model could have better helped answer the questions being considered. Analysis was not viewed only as an end product, but as part of an on-going design and refinement process. As a result, SPRED is a large-scale simulation model that is finding real and specific uses as an operational planning and policy evaluation management tool.

5. MODEL CALIBRATION AND APPLICATION

The National Petroleum Council (NPC) is a federally chartered and privately funded committee whose purpose is to advise, inform, and make recommendations to the Secretary of Energy with respect to any petroleum related matter submitted to it for consideration by the Secretary.

5.1. NPC Planning Factors

On November 7, 1983 the Secretary of Energy requested that the NPC study certain aspects of the SPR, including the maritime transportation of SPR oil under varying interruption scenarios. The NPC developed a set of marine transportation planning factors from historical petroleum shipping data provided by companies participating in the SPR study. These factors are summarized in Table 1. They have been used by the NPC to determine fleet resources necessary to satisfy specific petroleum throughput demands.

Table 1: NPC Marine Planning Factors

Loading Ports	Discharge Ports	Factor
Valdez	Puget Sound	1.51
	California	2.31
	Hawaii	2.67
	Puerto Armuelles	4.63
	Virgin Islands (via Cape)	12.07
Offshore U.S.W.C.	California	0.68
	Puerto Armuelles	2.90
	U.S. Gulf	5.13
	U.S. Atlantic Coast	5.72
	Puerto Rico	4.71
	V. I. (via Canal)	4.90
	V. I. (via Cape)	10.84
Puerto Armuelles	U.S. Gulf/P.R.	2.43
	U.S. Atlantic Coast	3.14
Chiriqui Grande	U.S. Gulf/P.R.	1.79
	U.S. Atlantic Coast	2.37
U.S. Gulf	Puget Sound	5.69
	California	4.96
	U.S. Atlantic Coast	2.32

The total deadweight tonnage (DWT) of the fleet dedicated to a particular transportation link necessary to deliver a given number of barrels of oil per day can be estimated by multiplying the barrel per day delivery requirement by the appropriate marine planning factor. These marine planning factors are a function of tanker steaming rates and round trip distances over the transportation links. For each link, the planning fractors can be translated into tanker turnaround times over the link according to the following:

$$(\text{NPC Factor}) \times b/d = \text{DWT}$$

rearranging terms:

$$d = [(\text{NPC Factor}) \times b] / \text{DWT}$$

where d = duration in days (= turnaround time)
b = Fleet capacity in barrels
DWT = dedicated fleet tonnage

For the purposes of this paper an average relationship of 8 barrels of crude oil per deadweight ton is used. Thus this equation reduces to:

$$d = 8 \times (\text{NPC Factor})$$

Table 2 presents the round trip mileages between the SPR/Sun marine terminal at Beaumont, Texas, and major refinery ports on the East Coast, California, and Puget Sound. Mean round trip mileages for each of these geographic areas have also been computed and presented. It is assumed for this study that round trip distances for all of the SPR marine terminals and receiving ports are the same. Since each SPR and receiving port is within several hundred of the mean for its geographic area, it is reasonable to apply the NPC planning factor for its corresponding geographic area to each of the ports in that area. For each geographic area, the NPC marine planning factors have been used to compute the estimated tanker turnaround times between that area and the SPR terminals. The computed turnaround times are also presented in Table 2.

Table 2: Tanker Turnaround (Round Trip) Days

	Gulf RT Mileage	NPC Factor	Turn-around Days
Atlantic Coast	3,590 (Mean)	2.32	18.56
New York	3,762		
Philadelphia	3,646		
Wilmington	3,646		
Norfolk	3,306		
California	9,383 (Mean)	4.96	39.68
Los Angeles	9,019		
San Francisco	9,747		
Puget Sound	11,197 (Mean)	5.69	45.52
Anacortes	11,103		
Seattle	11,291		

(from Sun Terminal, Beaumont, Texas)

5.2. Comparison of NPC Factors and SPRED

The turnaround times computed using the NPC marine planning factors have been plotted in Figure 2 (top line). This plot can be used to interpolate the turnaround time (per the NPC planning factor) over any round trip distance. Turnaround times computed from Figure 2 for major refinery ports in the U.S. are presented in Table 3. Also presented in Table 3 are the corresponding turnaround times computed using the SPRED model for the SPRED ship classes with a significant number of available vessels. It can be seen from these computations that SPRED computed turnaround times appear relatively insensitive to ship types and, therefore, an average turnaround

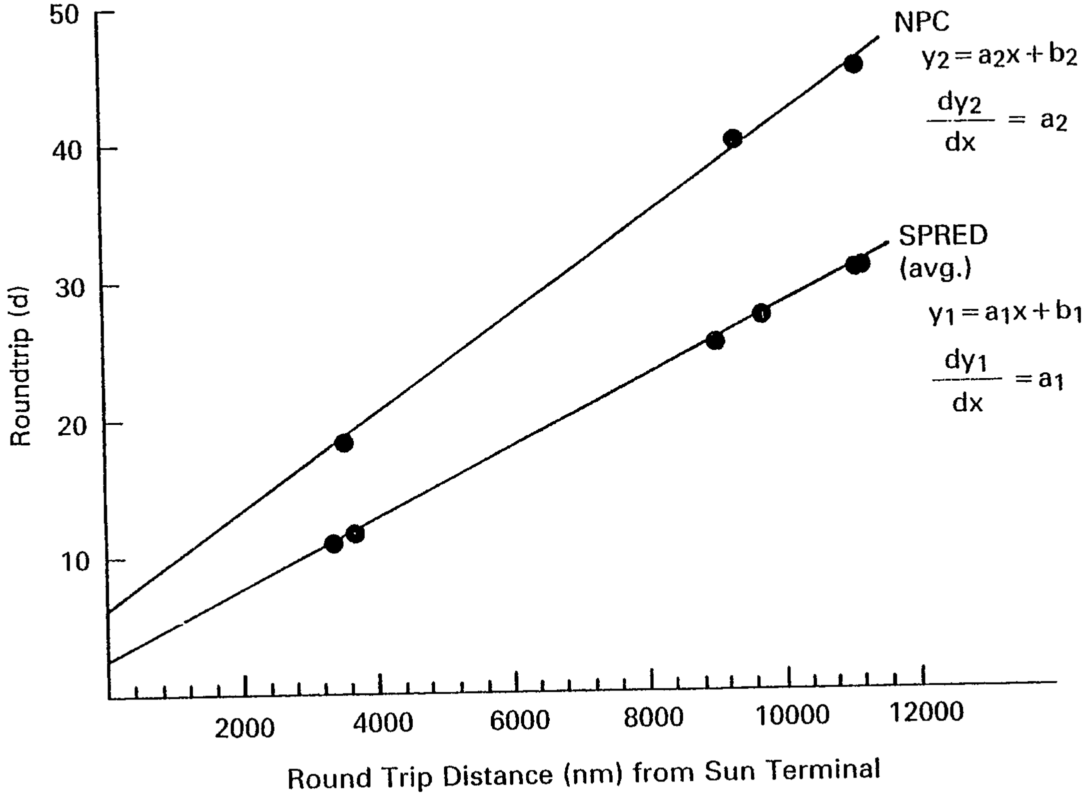

Figure 2: Tanker Transit (Turnaround) Time vs. Distance Travelled

time can be reasonably used to reflect turnaround times for all ship types.

Figure 2 (bottom line) presents plots of turnaround times over various round trip distances from the Sun Terminal which were computed using the SPRED model. It can be seen clearly from this Figure that there is a significant difference between turnaround times computed using the NPC developed planning factors and those computed using the SPRED model. Several considerations likely to account for the difference observed include:

* The SPRED input data base does not include explicit consideration of delays associated with bad weather, labor accommodations, safety inspections, market delays (e.g., wait for cargo destination assignments, wait at anchorage for cargo availability), Panama Canal transits, and preventative and corrective maintenance.

* The SPR marine distribution fleet as represented in the SPRED data base can be reasonably assumed to operate more efficiently (under emergency drawdown and distribution conditions) than is reflected in the NPC planning factors, which were derived from typical business-as-usual historical operating data.

The NPC planning factor analysis provides an historically based determination of the resources needed to distribute oil under business-as-usual conditions. SPRED provides an analytically rigorous evaluation of the capabilities of a specific set of shipping resources (a given ship fleet) to distribute reserve under emergency conditions. The difference observed between the two can be addressed and resolved in any one of several ways:

* A solution band for the distribution system petroleum throughput capability can be determined using both the NPC planning factors and SPRED. Actual emergency distribution capability can be assumed to fall within this band.

* Use the SPRED results as-is, cognizant of the greater efficiencies in distribution system operation possible during an emergency. While SPRED results may be viewed as optimistic, it is possible that emergency distribution capabilities may be closer to SPRED than to the BAU

Table 3: Days per Round Trip to Major Refinery Ports From Sun Terminal

Port	Round Trip Distance (nmi)	Days per Round Trip from NPC Planning Factor	Days per Round Trip by Ship Type# Computed with the SPRED Model: 4	5	6	7	8	9
Norfolk	3306	17.8	10.95	10.15	10.15	10.16	10.16	10.97
Wilmington	3646	19.2	11.54	11.05	11.06	11.53	11.03	11.55
Philadelphia	3646	19.2	11.45	11.05	11.09	11.05	10.98	11.46
New York	3762	19.5	11.92	11.28	11.60	11.36	11.44	11.99
Los Angeles	9019	38.2	25.12	24.40	24.96	24.00	24.88	25.84
San Francisco	9747	40.5	25.00	27.30	25.01	27.43	27.46	27.35
Anacortes	11103	45.5	31.20	29.84	30.48	30.40	29.76	30.40
Seattle	11291	46.2	30.26	30.30	30.45	30.38	30.47	30.39

Port	Avg Days per Round Trip (SPRED)	Difference: NPC and SPRED Days	% Diff##
Norfolk	10.42	7.4	42
Wilmington	11.29	7.9	41
Philadelphia	11.18	8.0	42
New York	11.60	7.9	41
Los Angeles	24.87	13.3	35
San Francisco	26.59	13.9	34
Anacortes	30.35	15.1	33
Seattle	30.39	15.8	34

SPRED ship type classes defined on the basis of size; see "Strategic Petroleum Reserve Distribution (SPRED) Model User Manual"

% difference = (NPC-SPRED)/NPC

based, historically derived NPC figures.

* Calibrate the SPRED model input data base to incorporate more of the BAU operational and market delays. This will result in SPRED output results which more closely approximate those results obtained through the use of the NPC factors, while retaining the operational realism and dynamic interaction of the SPRED simulation model.

No attempt has been made to evaluate the merits of each of the above alternatives. It is recognized, however, that the NPC planning factors represent a substantial body of real shipping experience and that, because of this, it may be useful to have a version of the SPRED data base calibrated to the NPC factors.

5.3. Calibration of SPRED Data Base

SPRED can be calibrated to the NPC factors if the plot of transit (turnaround) times computed using SPRED (in Figure 2) could be adjusted so that it corresponded to the plot for NPC derived transit times. To accomplish this, both the y intercept (b1) and the slope (a1) of the SPRED-derived plot must be adjusted to coincide with the y intercept (b2) and slope (a2) of the NPC planning factor derived plot. The a's correspond to the inverse of average tanker speed and the b's correspond to the sum of idle times at the nodes of each transportation link. The y-intercept correction is an additive adjustment while the slope correction is a multiplicative adjustment.

To calculate the necessary adjustments to a1 and b1, the difference (delta D) between the NPC derived and SPRED derived turnaround times has been plotted and is presented in Figure 3. The necessary adjustment beta to b1 is the y-intercept of the plot or approximately 4.2 days (100 hours). The additive correction to the SPRED data base can be accomplished by adding 100 hours to the turnaround time for each transportation link. The SPRED data base was adjusted by adding 50 hours to the clearance times at both the SPR terminals and the receiving terminals for all ship types. The necessary multiplicative adjustment alpha to a1, is the slope of the plot in Figure 3 or .025 hours/naut. mi. The uncorrected SPRED steaming rates for each ship type can thus be calibrated to the NPC planning factors.

Calibration of a version of the SPRED data base to the NPC planning factors has been implemented by modifying the SPRED ship data file data items regarding both terminal clearance times and tanker steaming rates. The NPC calibrated version of SPRED has been used to perform subsequent analyses of the adequacy of varying sized ship fleets to meet SPR distribution goals.

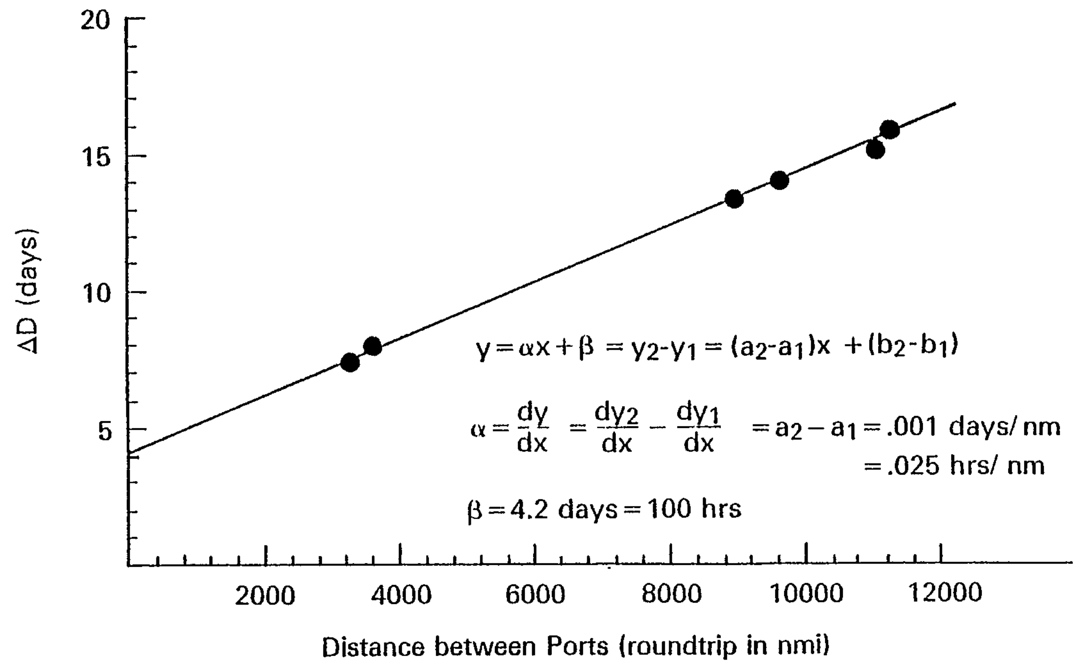

Figure 3: Differential Between Tanker Transit Times (NPC and SPRED)

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