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STEM: A SIMULATION MODEL OF SPACE SHUTTLE GROUND OPERATIONS

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To assess the feasibility of proposed launch schedules for operational flights of the Space Shuttle, a simulation model has been developed for Shuttle turnaround flow processing operations. Taking into account queueing delays due to the limited capacity of ground processing facilities, the model estimates flight starting dates which are required to meet a given launch schedule with a specified level of confidence. The results of an extensive sensitivity analysis based on the model indicate that the currently projected flight schedules are too optimistic and that the long-range ground turnaround time for an orbiter will substantially exceed the current goal of 28 days.

1. INTRODUCTION

Since the beginning of the Space Shuttle project, the National Aeronautics and Space Administration (NASA) has encountered many delays because of the research-and-development nature of the project and also because of limited funding. This makes effective project scheduling a crucial factor in all resource-allocation decisions. To evaluate alternative strategies for scheduling flights of the Space Shuttle, the Schedule Planning and Integration Office of the Johnson Space Center has developed a set of combined event-scheduling/process-interaction simulation models for various phases of the project. This paper reports on the development of the Shuttle Traffic Evaluation Model (STEM), a tool for analyzing the ground workflow which has been projected to occur during operational flights of the Space Shuttle.

1.1 Problem Statement

The Schedule Planning and Integration Office previously developed a model of the First Manned Orbital Flight (FMOF) using the Q-GERT simulation language (Pritsker 1979b). As an extension of this work, a model of subsequent operational flights was required. This model must take into account (a) the dependence of each flight upon previous flights, (b) limited availability of orbiters, (c) contention for ground processing facilities, and (d) variation in the activity completion times over successive flights.

1.2 Modeling Objectives

The main purpose of STEM has been to evaluate the feasibility of the Flight Assignment Manifest included in the Program Operating Plan (POP) for a fiscal year. A manifest specifies the scheduled launch date, the orbiter, and the payload assigned to each of a series of shuttle flights. To determine potential problem areas in proposed flight schedules, it has been necessary to perform a systematic investigation of the following factors: (a) delays in the delivery of new orbiters, (b) productivity increases due to "learning" over successive flights, and (c) uncertainty in the parameters describing individual activity times.

The development of a feasible flight schedule provides the basis for long-range fiscal planning.

STEM has been designed to generate the equipment need-dates for Solid Rocket Motors (SRMs) and External Tanks (ETs) which are required to support a given flight schedule. This means that budget projections can include the cost of production and facility expansion for these components.

2. MODEL DEVELOPMENT

2.1 System Description

Overall System Flow. The system to be modeled consists of the tasks and resources required for each flight of the Space Shuttle. Figure 2.1 shows the overall flow of activities for a single flight. A short description of each of the major activities is given below:

1. Vehicle Assembly. In this activity, the components of the spacecraft are finally joined. These components include the solid rocket motors, the solid rocket boosters (SRBs), the external tank, and the orbiter. Shuttle assembly is performed on the Mobile Launcher Platform (MLP). Assembly starts with the stacking of the right and left SRMs on the MLP. After the SRMs are in place, the SRBs are mated with the SRMs; this involves stacking each booster on top of its corresponding SRM. (The SRBs contain the solid rocket fuel for the SRMs.) The external tank is then attached to the left and right SRB assemblies. Finally the orbiter is mated directly to the external tank. Following assembly and checkout on the MLP, the Shuttle is rolled out to the launch pad using a Mobile Crawler Transporter.

2. Prelaunch Activities. This includes the checkout for all shuttle systems, the movement of the shuttle to the launch pad on the MLP, the installation and servicing of payloads on the pad, fueling of the shuttle, and the countdown.

3. Payloads Installed on Pad. Payloads utilizing propulsive upper stages are placed in the orbiter at the launch pad using the payload changeout room in the Rotating Service Structure (RSS).

4. Launch and Flight. This activity includes the launch and execution of the mission while in orbit.

5. SRB Recovery. The SRB assemblies are parachuted back to earth, where they are recovered by ships.

6. SRB Refurbish. The SRBs and SRMs are cleaned and serviced so that they can be reused on later flights. The SRMs are reloaded with solid propellant and then reassembled with forward and aft assemblies.

7. Landing. For the first 4 flights, the orbiter will land at Edwards Air Force Base in California; subsequent flights launched from Kennedy Space Center (KSC) will land at the KSC landing site. (At a later date there will also be launches from Vandenburg Air Force Base in California.) This landing activity includes a presafing operation on the runway immediately after landing.

8. Safing. After the presafing activity is complete, the orbiter is towed to the safing area, where the payload is removed, pressurized containers and fuel cell reactants are vented, and the hazardous fuel modules are removed.

9. Orbiter Checkout and Maintenance. During this activity the orbiter undergoes inspection, maintenance, and servicing. This operation is performed in the Orbiter Processing Facility (OPF), and it sometimes includes the installation of a payload (for example, Spacelab). When operations have been completed in the OPF, the orbiter is towed to the Vertical Assembly Building (VAB), where it is coupled to the ET/SRB assembly. This completes the shuttle assembly.

10. External Tank Delivery. External tanks are only used once; they disintegrate on reentry into the earth's atmosphere. After arrival from the manufacturer, ETs are checked out and processed before being moved to the VAB where they are attached to the SRB assemblies waiting on the MLP.

11. New SRB Deliveries. To compensate for the length of SRB refurbishment times and for the limited operational life of each SRB assembly, regular deliveries of new SRBs will also be made.

Overall ground operations encompass a series of scheduled shuttle flights which are linked together by their shared resources. An example of this is the orbiter; it is reused after a flight, and any events which affect the orbiter on one flight will also affect subsequent flights. Other shared resources include processing facilities such as the OPF, the VAB, the firing room, and the launch pad. Several flights may compete simultaneously for these facilities if there are several orbiters in process or if some flights have been delayed. Current estimates of the flight processing capacity (in total number of flights per year) for individual facilities are as follows: OPF, 20; MLP, 8; VAB, 12; launch pad, 26. New facilities are projected to become operational according to the following schedule: OPF-2, August 1982; MLP-2, September 1982; VAB-2, June 1983; launch pad B, September 1985. Clearly the model will have to incorporate these additions when they occur. This concludes a very brief description of the shuttle workflow; a more detailed explanation may be found in (NASA 1976).

OVERALL SYSTEM FLOW

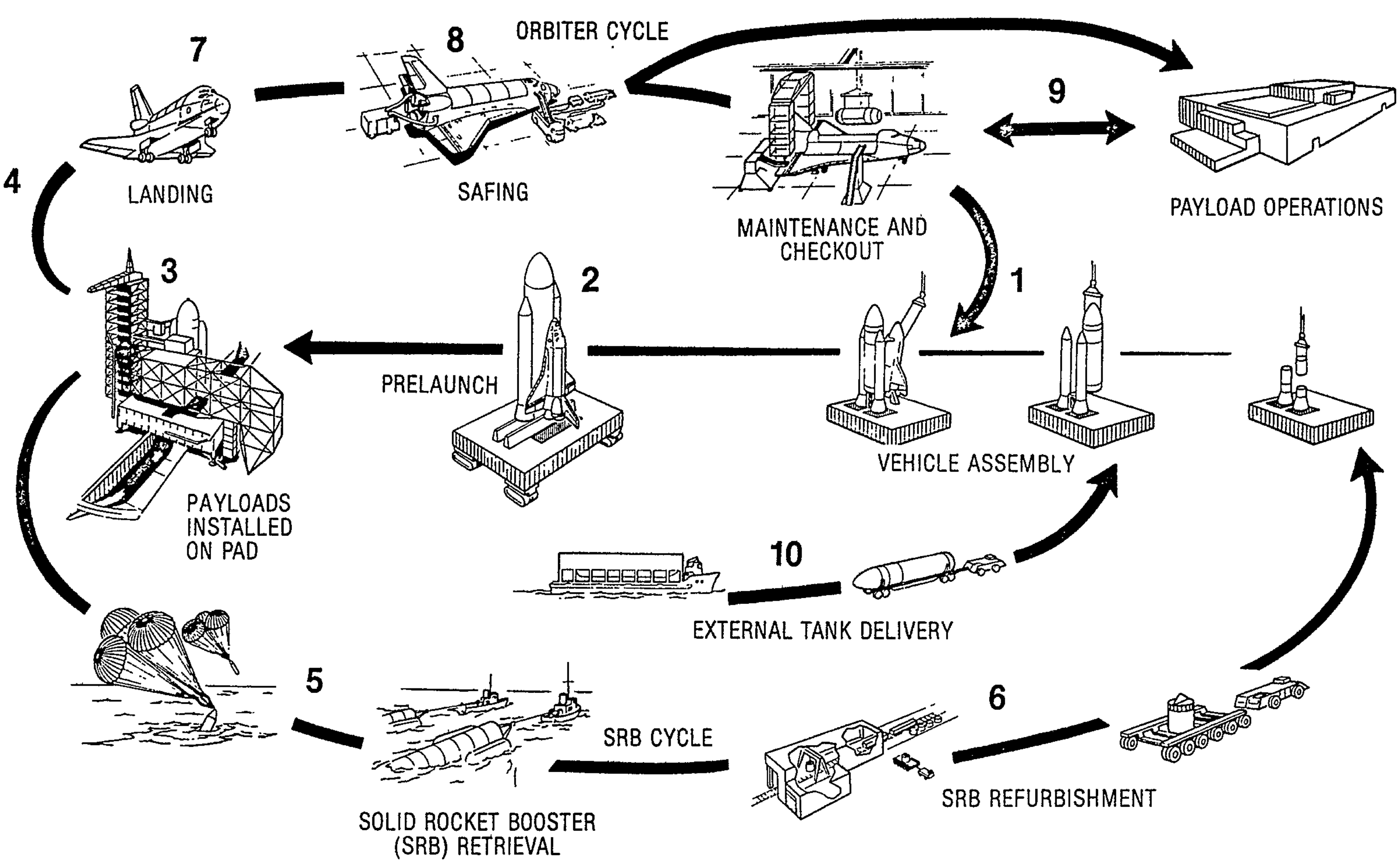


FIGURE 2.1

System Boundaries. The processes for manufacturing new orbiters, SRBs, and ETs as well as the refurbishing operations for SRMs and SRBs are considered to lie outside the system. Orbiters are simply brought into the system at specific dates. ET, SRM and SRB assemblies are assumed to be available when needed. Equipment need-dates (that is, the times at which ETs, SRBs and SRMs are needed for a particular flight schedule) are used to estimate the corresponding production timetable required to meet the launch schedule. This means that the model does not include recycling of SRBs and SRMs. Payloads are also assumed to be available when they are needed by a flight. However, payload requirements will not be predicted as with the ETs, SRBs and SRMs; there will always be enough available payloads so that substitutions can be made to avoid delaying the launch date of a flight.

2.2 Model Design Issues

After the boundaries of the system had been defined, the next step was to decide on the level of detail to include in the model. An assessment of the trade-off between simplicity and validity of the final product led to the incorporation of the following features into the model:

1. Orbiter maintenance and checkout operations for a given flight can be delayed by slippage in orbiter delivery dates, by unavailability of a particular orbiter, or by delays in the launch dates of preceding flights.

2. Activity times can include random variations as well as the learning phenomenon. Activity sampling uses triangular distributions whose parameters (minimum, maximum, and mode) decline according to an appropriate learning curve. In standard learning-curve terminology, the flight number represents the cumulative unit number for the learning function describing a particular activity (Yelle 1979).

3. Several flights can be in various stages of completion simultaneously, and queueing delays may be encountered by some of these flights due to competition for any of the following limited resources: the MLP, the SRB assembly facility, the ET assembly facility, the OPF, and the launch pad.

4. A "backoff" procedure compensates for queueing-related flight delays in order to provide a specified probability of meeting a proposed schedule of launch dates. This procedure estimates the corresponding flight start dates which are required to meet the launch schedule with the specified level of reliability.

Because the description of system operation was given essentially in terms of a complex sequence of activities constituting the shuttle launch process, the selection of an appropriate vehicle for implementing STEM naturally focused on simulation languages with process-interaction capability (Kiviat et al. 1973; Pritsker 1979a, b; Schriber 1974). However, it was clear that an event-scheduling approach (Fishman 1978, Kiviat et al. 1973, Pritsker 1979a) would facilitate the development of the activity-sampling scheme, the backoff procedure, and the logic for controlling orbiter availibility. The SLAM simulation language (Pritsker 1979a) was selected because it appeared to offer the greatest flexibility for combined event-scheduling/process-interaction simulation. In addition, the SLAM input/output procedures allowed the integration of the following features into the overall model:

1. A set of date conversion routines to provide for input and output of all dates in an easy-to-read MM.DDYYYY format;

2. An auxiliary program EQUIP to generate equipment manufacturing schedules based on the flight start dates estimated by the SLAM model; and

3. An auxiliary program GANTT to plot Gantt charts corresponding to the equipment manufacturing schedules generated by EQUIP.

3. MODEL DESCRIPTION

The SLAM implementation of STEM consists of the following elements: (a) a set of SLAM input statements describing a network model of the system workflow, (b) the necessary event-oriented support routines, and (c) a data file specifying the proposed launch schedule to be evaluated. As shown in Figure 3.1, the network model represents both the resources and the sequence of activities required for each flight; a feedback loop to the initial node labeled STRT allows multiple replications of the proposed flight schedule to be performed.

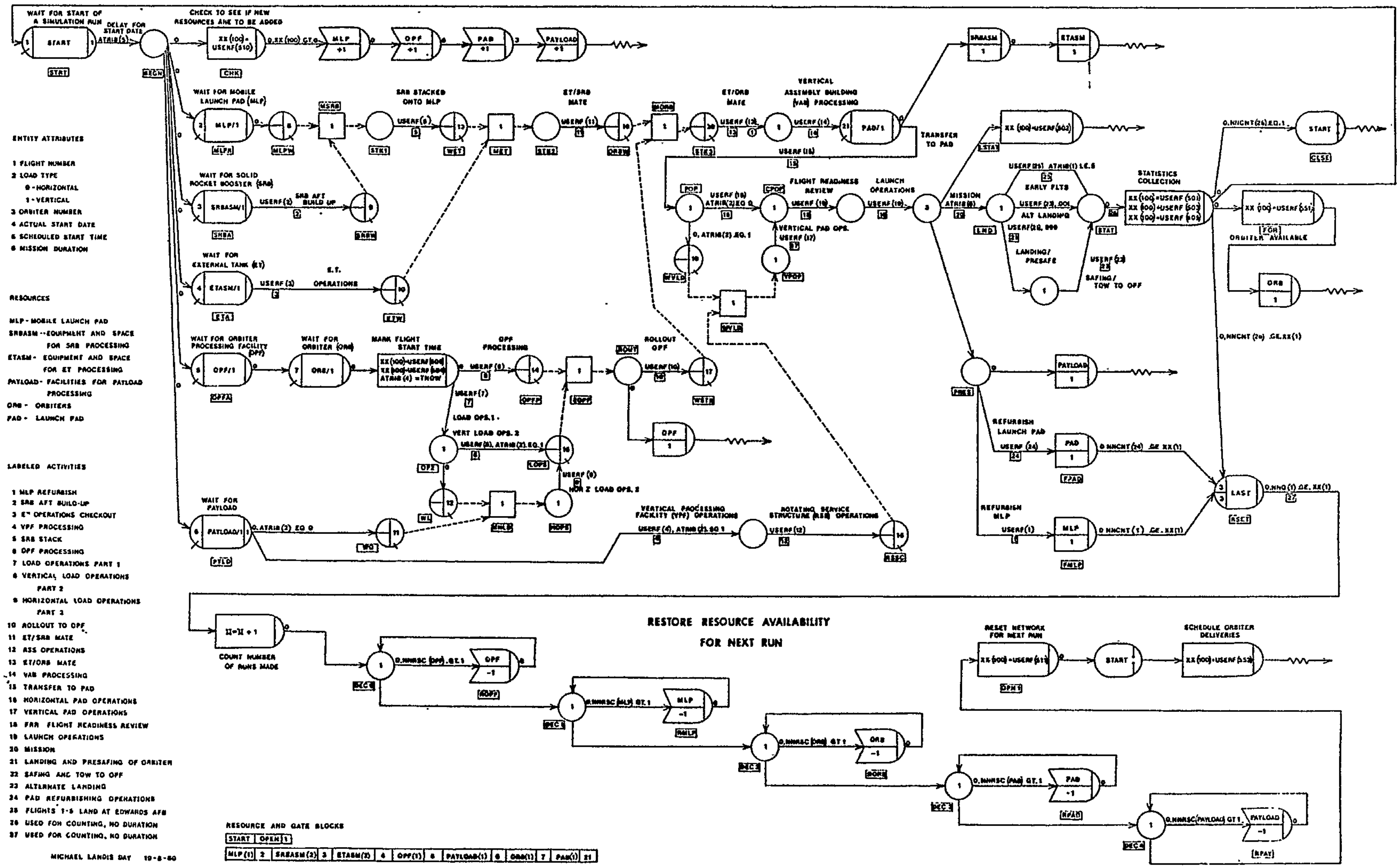
The model executes in the following manner:

1. The launch schedule is read in, and entities representing individual flights are set up. With respect to each nontrivial activity, parameters are established for the associated learning curve and for the corresponding family of triangular distributions. In particular, let a_i, m_i and b_i respectively denote the minimum, modal, and maximum times for a given activity when it is performed on flight i. With a learning rate r ($0 < r \leq 1$) specified for this activity, the parameters a_i, m_i, and b_i are calculated according to the classical power-function model (Conway and Shultz 1959, Yelle 1979).

$$\left.\begin{aligned} a_i &= a_1 \cdot i^c \\ m_i &= m_1 \cdot i^c \\ b_i &= b_1 \cdot i^c \end{aligned}\right\} \text{ for every flight } i \geq 1, \quad (3.1)$$

where the learning index c is given by

$$c = \log(r)/\log(2).$$



ENTITY ATTRIBUTES
1 FLIGHT NUMBER
2 LOAD TYPE
0 - HORIZONTAL
1 - VERTICAL
3 ORBITER NUMBER
4 ACTUAL START DATE
5 SCHEDULED START TIME
6 MISSION DURATION
RESOURCES
MLP - MOBILE LAUNCH PAD
SRBASM -- EQUIPMENT AND SPACE FOR SRB PROCESSING
ETASM - EQUIPMENT AND SPACE FOR ET PROCESSING
PAYLOAD - FACILITIES FOR PAYLOAD PROCESSING
ORB - ORBITERS
PAD - LAUNCH PAD
LABELED ACTIVITIES
1 MLP REFURBISH
2 SRB AFT BUILD-UP
3 ET OPERATIONS CHECKOUT
4 VPF PROCESSING
5 SRB STACK
6 OPF PROCESSING
7 LOAD OPERATIONS PART 1
8 VERTICAL LOAD OPERATIONS PART 2
9 HORIZONTAL LOAD OPERATIONS PART 2
10 ROLLOUT TO OPF
11 ET/SRB MATE
12 RSS OPERATIONS
13 ET/ORB MATE
14 VAB PROCESSING
15 TRANSFER TO PAD
16 HORIZONTAL PAD OPERATIONS
17 VERTICAL PAD OPERATIONS
18 FRR FLIGHT READINESS REVIEW
19 LAUNCH OPERATIONS
20 MISSION
21 LANDING AND PRESAFING OF ORBITER
22 SAFING AND TOW TO OPF
23 ALTERNATE LANDING
24 PAD REFURBISHING OPERATIONS
25 FLIGHTS 1-5 LAND AT EDWARDS AFB
26 USED FOR COUNTING, NO DURATION
27 USED FOR COUNTING, NO DURATION
MICHAEL LANDIS DAY 10-8-80
WAIT FOR START OF A SIMULATION RUN
DELAY FOR START DATE
CHECK TO SEE IF NEW RESOURCES ARE TO BE ADDED
WAIT FOR MOBILE LAUNCH PAD (MLP)
WAIT FOR SOLID ROCKET BOOSTER (SRB)
WAIT FOR EXTERNAL TANK (ET)
WAIT FOR ORBITER PROCESSING FACILITY (OPF)
WAIT FOR ORBITER (ORB)
MARK FLIGHT START TIME
WAIT FOR PAYLOAD
SRB STACKED ONTO MLP
ET/SRB MATE
ET/ORB MATE
VERTICAL ASSEMBLY BUILDING (VAB) PROCESSING
TRANSFER TO PAD
FLIGHT READINESS REVIEW
LAUNCH OPERATIONS
MISSION
EARLY FLTS
ALT LANDING
LANDING/PRESAFE
SAFING/TOW TO OFF
STATISTICS COLLECTION
ORBITER AVAILABLE
OPF PROCESSING
ROLLOUT OPF
VERTICAL PROCESSING FACILITY (VPF) OPERATIONS
ROTATING SERVICE STRUCTURE (RSS) OPERATIONS
REFURBISH LAUNCH PAD
REFURBISH MLP
RESTORE RESOURCE AVAILABILITY FOR NEXT RUN
COUNT NUMBER OF RUNS MADE
RESET NETWORK FOR NEXT RUN
SCHEDULE ORBITER DELIVERIES
RESOURCE AND GATE BLOCKS

FIGURE 3.1

2. Phase I of STEM operation begins by releasing all of the flight entities waiting at the initial node STRT in order to simulate a single realization of the proposed flight schedule. The simulation clock is set to read 0.0 at the start of flight 1. The lag L(i) between the scheduled launch dates for the 1st and ith flights is then used as a first-cut estimate of the maximum allowable delay between the starting times for those flights. This procedure fixes the simulated starting times for all flights in Phase I relative to the start of flight 1.

3. When all of the scheduled flights have been completed and the corresponding entities have returned to the node STRT, each system resource is restored to its initial capacity and another replication of the proposed schedule is executed. This process is repeated until satisfactory precision is obtained for a set of estimators used in the backoff procedure. Let p denote the desired probability of meeting the scheduled launch date for flight i, and let X(i,j) denote the jth replication $(i \leq j \leq n)$ of the start-to-launch delay for flight i. If X(i,j), is normally distributed, then the sample statistics

$$\bar{X}(i) \equiv (1/n) \sum_{j=1}^{n} X(i,j)$$

$$S(i) \equiv \{[1/(n-1)] \sum_{j=1}^{n} [X(i,j)-\bar{X}(i)]^2\}^{1/2}$$

can be used to construct the maximum likelihood estimator $\hat{x}_p(i)$ for the pth quantile $x_p(i)$ of the start-to-launch delay for flight i (Naylor 1980):

$$\hat{x}_p(i) = \bar{X}(i) + z_p \cdot S(i) \cdot [1-(1/n)]^{1/2} \quad (3.2)$$

[Note that in equation (3.2), z_p denotes pth quantile of the standard normal distribution and thus cuts off a tail of size p in the left-hand portion of that distribution.] The standard error of $\hat{x}_p(i)$ is approximately given by (Naylor 1980):

$$SE[\hat{x}_p(i)] \simeq$$

$$S(i) \cdot \{[1 + (n-1) \cdot z_p^2/(2n)]/n\}^{1/2}. \quad (3.3)$$

In many STEM runs, the replication count n is taken sufficiently large to insure that $SE[\hat{x}_p(i)] < 1$ day for each flight i.

4. The backoff procedure applies the results of step 3 to estimate the latest starting date for the ith flight which will provide the specified probability p of lift-off by the scheduled launch date. This starting date for flight i is obtained by backtracking $\hat{x}_p(i)$ days from the scheduled launch date for that flight. The simulation clock is again set to read 0.0 at the start of flight 1. Figure 3.2 illustrates how the backoff equation

$$\hat{D}(i) = L(i) + \hat{x}_p(1) - \hat{x}_p(i) \quad (3.4)$$

yields an estimate $\hat{D}(i)$ of the maximum allowable delay D(i) between the starting times for the 1st and ith flights in terms of the scheduled lag L(i) between the corresponding launch dates. This procedure establishes the simulated starting times for all flights in Phase II relative to the start of flight 1.

5. Phase II of STEM operation uses the new starting-time delays $\hat{D}(i)$ to generate a new set of replications for the proposed flight schedule. This allows a direct evaluation of the effectiveness of the backoff procedure in meeting scheduled launch dates with the desired level of reliability. (It may be necessary to reiterate phase I to achieve an adequate backoff interval for each flight.)

6. The new schedule of flight start dates is combined with estimated production rates for ETs, SRBs, and SRMs to construct production timetables and Gantt charts showing the dates by which each piece of equipment must be started and finished in order to avoid equipment-related flight delays.

4. DATA ACQUISITION

Estimates of minimum activity times were based on a detailed analysis of the flight 2 workflow as projected by scheduling personnel at the Kennedy Space Center. Thus the parameter a_2 was determined for each activity individually. The corresponding modal activity time m_2 was obtained by applying a standard multiplicative factor f to the estimated minimum

$$m_2 = f \cdot a_2. \quad (4.1)$$

To force the mean duration of each activity to coincide with its mode, the corresponding maximum b_2 was symmetrically placed with respect to the mode.

$$b_2 = m_2 + (m_2-a_2) = (2f-1) \cdot a_2 . \quad (4.2)$$

As will be discussed later, the factor f was subjected to an extensive sensitivity analysis. In many STEM runs the value f = 1.25 was used.

An appropriate learning model was required in order to estimate activity-time parameters for other flights. As an alternative to the conventional power function

$$y_i = y_1 \cdot i^c \quad , \tag{4.3}$$

consideration was also given to the exponential learning model (Pegels 1969)

$$y_i = k \cdot g^i + d. \tag{4.4}$$

This latter functional form is appealing because it allows for the possibility of plateauing (Yelle 1979) -- that is, a limiting or standard time d can be included in the learning model. However, difficulties were encountered in estimating d for each activity; and this complicated both the estimation and interpretation of the parameters k and g. As a result, the exponential model was discarded in favor of the power-function model.

Estimated learning rates for various activities were based on consideration of physical limitations as well as workflow analysis. Because they are mechanically constrained operations not subject to substantial improvement, activities involving the mating of major shuttle components, load/unload operations on payloads, and launch pad refurbishment were assigned a 90% learning rate. No Learning (that is, a rate of 100%) was assumed for activities involving interfacility transfers of major shuttle components and for orbiter landing and safing operations. A 62% learning rate was established for all other activities using the detailed KSC projections of total start-to-launch times $\{y_i : 2 \leq i \leq 5\}$ for flights 2-5 together with the long-range goal of a 2-week ground turnaround for flight 33 (y_{33} = 28 days). After a logarithmic transformation was applied to the model (4.3), the resulting least-squares estimates c= -0.689 led to the learning rate $\hat{r}$ = 0.620. Omitting the point corresponding to flight 33 led to an estimated learning rate of 55%. This figure was subsequently used an an optimistic rate for the activites with fast learning: in worst-case scenarios, a pessimistic rate of 70% was assumed for those activities.

Data concerning hardware availability were obtained from the Marshall Space Flight Center in the form of projected manufacturing schedules for SRMs, SRBs, and ETs. Orbiter delivery dates were obtained from the POP Flight Assignment Manifest. Periods of orbiter availability were modified where necessary to reflect requirements of the Defense Department.

5. MODEL VERIFICATION AND VALIDATION

Several verification techniques were used to detect and correct discrepancies between the intended and actual execution processing performed by STEM (Law 1979). Structured walk-throughs were used to review both the overall design of the network model and the detailed implementation of the support routines. The standard SLAM trace was used extensively to debug the network model, and a modified version of the SLAM trace was later developed to track the movement of a single flight-entity through the network. Systematic variation of selected input parameters throughout the range of feasible values revealed several errors. When for example the backoff percentage p in equation (3.2) was initially varied over the range [0.05,0.95], a coding error was uncovered in the numberical approximation (Abramowitz and Stegun 1964) to the inverse standard normal distribution $z_p = \Phi^{-1}(p)$. By driving the activity-time factor f down to 1.00, all activity times were forced to assume their minimum values [see equations (4.1) and (4.2)]. With deterministic activity times, the start-to-launch delay was calculated manually for a single flight to check the corresponding STEM output; over several flights, this approach allowed manual verification of the logic for learning-curve calculations.

To validate STEM as a sufficiently accurate representation of shuttle operations for the purposes of the study, fewer clear-cut techniques were available (Naylor and Finger 1967, Van Horn 1971). Because many of the modeled activities are still in the development stage, goodness-of-fit testing on individual activity durations was not possible However, the distributional assumptions underlying the backoff procedure [equations (3.2) through (3.4)] were examined in some detail. Under the assumption of normally distributed start-to-launch delays $\{X(i,j) : 1 \leq j \leq n\}$ for flight i, exact and approximate point and interval interval estimators for the pth quantile $x_p(i)$ were developed (Dyer et al. 1977, Naylor 1980, Owen 1968). In addition, alternative nonparametric estimators for $x_p(i)$ were devised (Kendall and Stuart 1979, Naylor 1980) Since the start-to-launch delays X(i,j) for the jth replication of flight i is a sum of many queueing and activity delays and since none of these delays dominate the sum, a central-limit type of effect may be expected to induce approximate normality in X(i,j). To test this hypothesis, the Shapiro-Wilk normality test (Shapiro and Francia 1972, Shapiro and Wilk 1965, Weisberg and Bingham 1975) was applied separately to the data set $\{X(i,j) : 1 \leq j \leq n\}$ for each flight i, where $1 \leq i \leq 40$. Because no significant departures from normality were detected at the 1% level in any of the 40 tests, the backoff procedure defined by equations (3.2) through (3.4) was used in all subsequent runs.

From a broader perspective, the validation of STEM consisted largely of continual interaction with knowledgeable NASA personnel. Their feedback on the reasonableness (or unreasonableness) of STEM output formed the basis for all revisions and extensions of the model.

6. EXPERIMENTAL RESULTS

To assess the overall feasibility of a proposed flight schedule, STEM outputs were used in two different ways. Analysis of the Operational Flight Tests (flights 1-4) concerned the effects of the following factors on the simulation-generated launch dates:

1. Delays in the completion of the FMOF,

2. Production rates for flight hardware, and

3. The delivery date for orbiter 099.

With respect to the operational flights (that is, flight 5 and beyond), the focus shifted to the following issues:

1. The ultimate achievement of a 28-day ground turnaround time,

2. The effects of slippage in subsequent orbiter deliveries, and

3. The actual buildup rate for flights in each fiscal year.

To carry out such assessments, NASA personnel frequently used STEM-generated "spot charts" showing the estimated mean launch date for each flight and the orbiter assigned to that flight. Figure 5.1 displays the spot chart for a base case with backoff percentage p = 50%, activity-time factor f = 1.25, learning rate r = 62%, and a 3-month delay in the delivery of each of the orbiters 099, 104, and 105. Figure 5.2 shows a Gantt chart of the ET production schedule required to support this scenario. The results indicate that delays in completion of the Operational Flight Tests make the on-time delivery of orbiter 099 less critical than was previously thought. [Actually, there have also been delays in the completion of the new processing facilities (OPF-2, MLP-2, VAB-2, PAD-B) which will be required.] For the operational flights, turnaround time does not decline as rapidly as expected; moreover, the flight buildup is substantially slower than required by the POP 80-2 Flight Assignment Manifest. Figure 5.2 clearly indicates that a large number of in-process ETs are required to support shuttle operations.

Investigation of the sensitivity of the model to changes in learning rates, activity times, and hardware availability involved the selection and execution of a large number of alternative cases. Figure 5.3 displays the long-range effects on flight buildup obtained by modifying the base case with activity-time multipliers f = 1.00, 1.25, and 1.50. Figure 5.4 shows similar effects when deviations from the base case involve the learning rates r = 55%, 62% and 70%. Finally, the impact of 0-, 3-, and 6-month delays in the delivery dates for each of the orbiters 099, 104, and 105 is charted in Figure 5.5. It appears that the flight buildup will reach the level prescribed in the POP 80-2 Flight Assignment Manifest--

1. By fiscal year 1985 if f = 1.00, r = 62%, and if there are no delays in orbiter deliveries;

2. By fiscal year 1986 in the base case; and

3. By fiscal year 1987 in the worst case where f = 1.50, r = 70% and there are 6-months orbiter delays.

7. CONCLUSIONS

The Shuttle Traffic Evaluation Model has been used extensively by NASA personnel for evaluation of proposed Flight Assignment Manifest, for budget analysis, and for projection of future hardware requirements. In addition, the model incorporates some innovative techniques for project risk analysis which can be generalized and applied to other problems.

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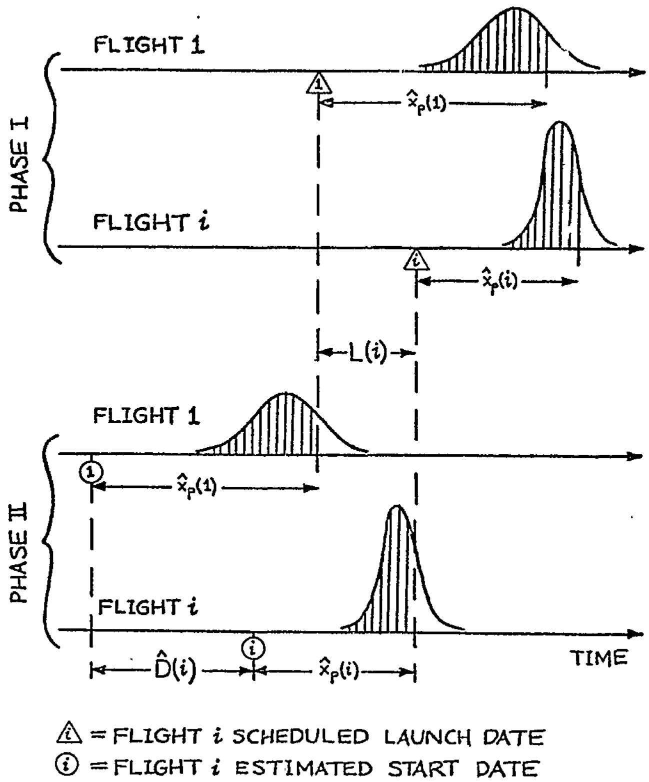

FIGURE 3.2

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              I                 I                 I                 I                 I                 I
              I       81        I       82        I       83        I       84        I       85        I
              I                 I                 I                 I                 I                 I
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
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ORBITER
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OV-102         01          02          03      04      07    09   10   12   15   17  1920  23  26  29  33 3639
OV-099                                         05      06    08    11  1314  16  18  21  22  25  27  30 3234  37
OV-104                                                                                     24    28  31 3538  40
```

AVERAGE LAUNCH DATES

FLT	LAUNCH	ORB	FLT	LAUNCH	ORB	FLT	LAUNCH	ORB
1	3.231981	102	2	12.301981	102	3	7.201982	102
4	1.121983	102	5	1.191983	99	6	5.281983	99
7	6.041983	102	8	9.191983	99	9	9.231983	102
10	12.131983	102	11	1.031984	99	12	3.191984	102
13	4.021984	99	14	5.281984	99	15	6.261984	102
16	8.041984	99	17	9.141984	102	18	10.211984	99
19	12.021984	102	20	1.271985	102	21	12.311984	99
22	2.241985	99	23	4.101985	102	24	4.291985	104
25	4.251985	99	26	6.151985	102	27	6.121985	99
28	7.121985	104	29	8.131985	102	30	8.021985	99
31	9.151985	104	32	10.021985	99	33	10.131985	102
34	11.151985	99	35	11.131985	104	36	12.111985	102
37	1.061986	99	38	12.251985	104	39	1.181986	102
40	2.061986	104						

FIGURE 5.1

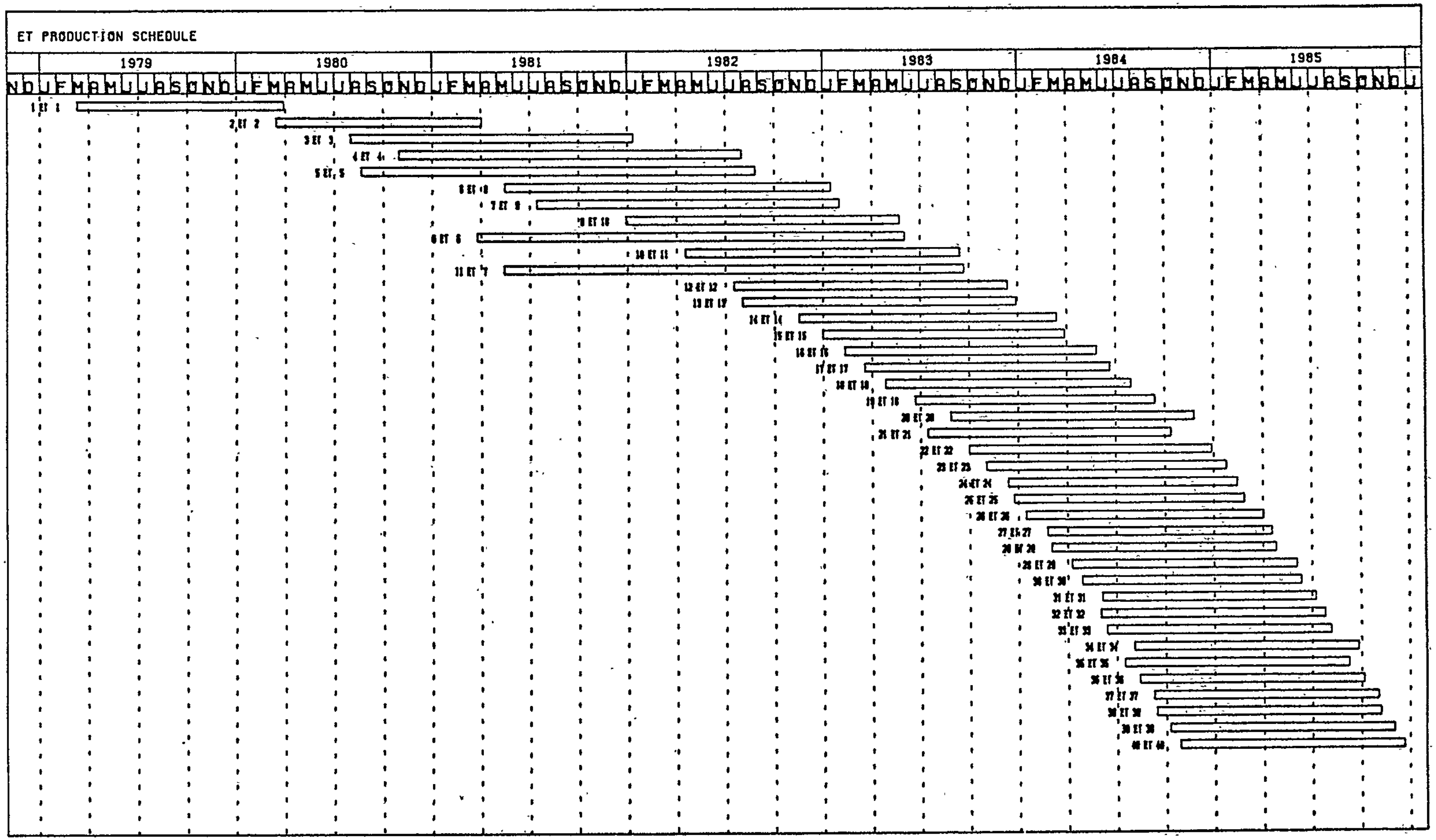

FIGURE 5.2

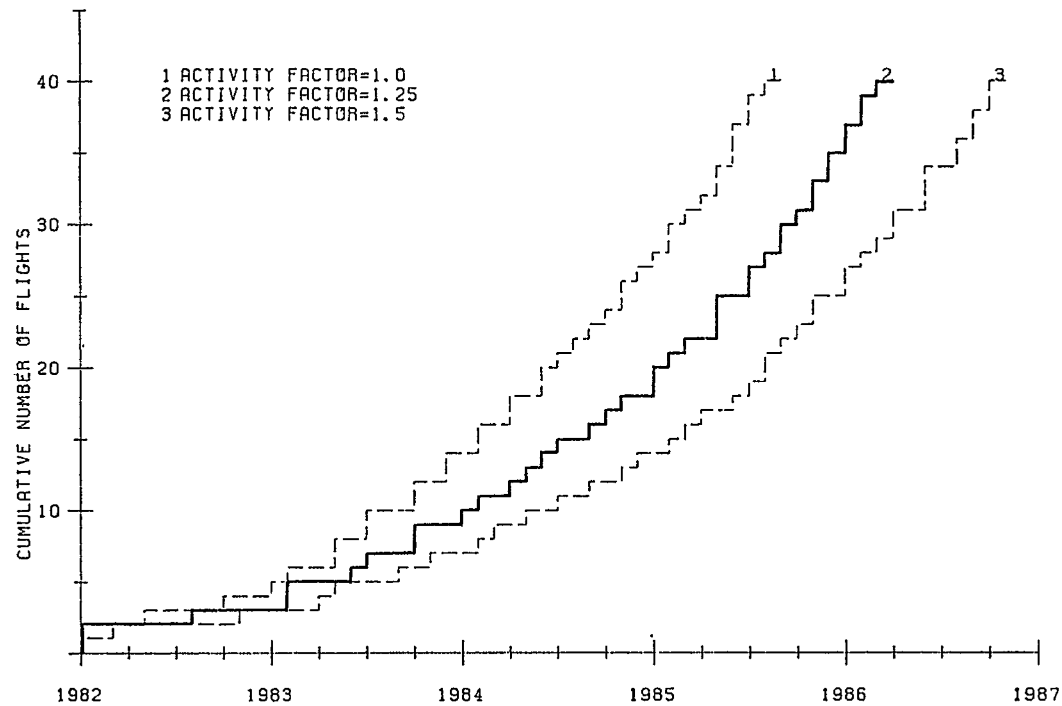

Figure 5.3

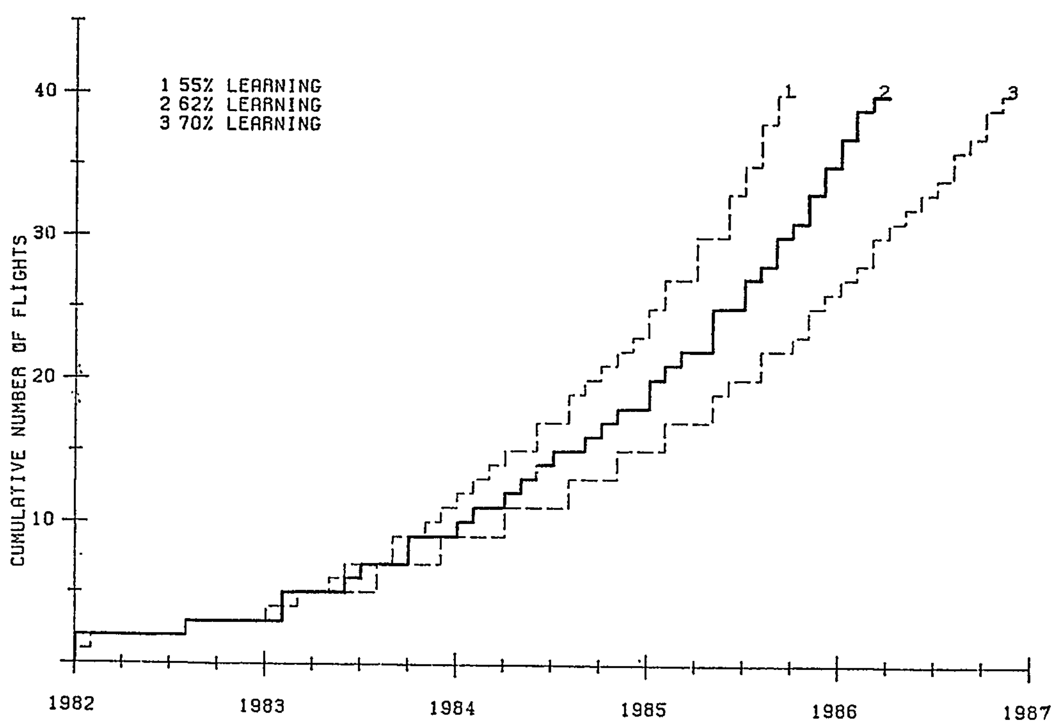

Figure 5.4

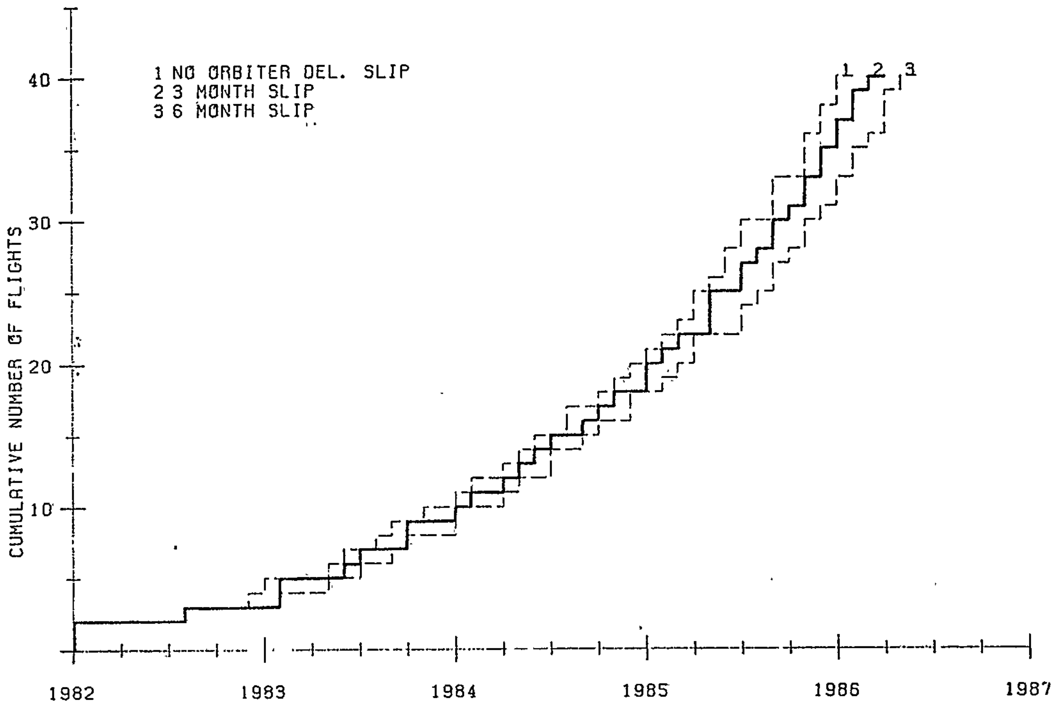
1 NO ORBITER DEL. SLIP
2 3 MONTH SLIP
3 6 MONTH SLIP
CUMULATIVE NUMBER OF FLIGHTS
40
30
20
10
1
2
3
1982
1983
1984
1985
1986
1987

Figure 5.5