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1970

HOSPITAL BLOOD BANKING:
AN INVENTORY SYSTEM FOR
DISTINGUISHABLE, PERISHABLE
ITEMS WITH PRIOR RESERVATIONS

by

MANUS RABINOWITZ

A dissertation submitted to the
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PREFACE

The study deals with the establishment of a model of a hospital blood bank system. Its major purpose was to investigate some of the controllable variables associated with blood bank inventory policies in view of the special problems of hospital blood banking.

An exhaustive investigation of the Mount Sinai Hospital¹ Blood Bank system was performed to obtain actual data on such factors as replenishment policies, age of blood, requests, cross-matching, requisitions, returns and reservation cancellations. Blood type and patient classifications were recognized in their analysis.

Special properties inherent in blood banking systems are represented in the model. These include:

1. The age limitation on blood usage;
2. Crossmatching and reservation;
3. Variability in requests for blood;
4. Failure to utilize blood reservations;
5. Relative prevalence and scarcity of blood types;
6. The age of blood upon receipt;
7. Patient identification and association with his demand.

¹The Mount Sinai Hospital, 100th Street and Fifth Avenue, New York, New York 10029.

The principal method of investigating these problems was through computer simulation of the blood bank system. Through such a simulation, it was sought to establish more efficient operating policies for blood bank inventory control and to provide a vehicle for detailed examination and experimentation with alternative policies, both new and existing, relating to the subject.

The criteria for evaluation of inventory policies are many and diverse. The main measures considered in this treatment were those of shortages and wastage, variations in workload, and variations in demand on the blood supply. Evaluations using the age of transfused blood are also possible with this model.

Detailed comparisons with models used by other researchers are also presented. Summarizations of previous work include their limitations and recognize that they were concerned only with the problem of "optimal" inventory level.

The major emphasis in this research is the consideration of three proposed operating policies for control of blood wastage, while using inventory level to control shortages. These policies are discussed and evaluations of them were obtained using the simulation model.

The first approach makes a unit of blood available to either of two patients by performing two crossmatches, so that while reserved either can requisition it. In addition, other

steps are taken so that there is no possibility of a unit not being available to either patient. This method, called double-crossmatching, can be used to reduce wastage of blood by appropriately assigning the pair of units available to each patient. The effects of this policy on wastage and workload under different conditions are evaluated.

The second policy provides for the recognition of any classes of patients whose usage patterns indicate that they are more likely to use blood previously reserved for them. If these patients can be identified, and if the older blood is crossmatched and reserved for them, this policy can also be used to effect a reduction in blood wastage.

The third policy recognizes that some blood types, in particular Rh negative blood, are relatively rare. Maintenance of adequate inventory to provide protection against shortages results in much more wastage of these blood types. If, however, some of these units were permitted to be used by Rh positive patients, this wastage could be reduced. Evaluation of the conditions under which this would be desirable, and its effect on the supply of the rarer blood types, are presented.

Appendices to this report deal with data collection, verification, analysis and their presentation. In addition, the simulation program listing, a detailed flow chart, sample output, and

input requirements are appended. Technical details relating to the estimation of statistical parameters, testing the fit of theoretical models, and the generation of random events are also given.

Although the concepts contained in this report are specifically directed to the blood bank inventory problem, they can be applied to any inventory situation characterized in the following requirements:

1. Prior reservation of demand whether required as in a blood bank or for customer convenience.
2. Differentiation between items in inventory, based on some measure of desirability, but where several items are capable of effectively satisfying demand.
3. Items whose usefulness lasts for only a limited period of time.

Examples of problems which have the above characteristics are given below, including the item demanded, the different products available, and the nature of the item obsolescence:

1. Theater tickets, in the orchestra, mezzanine, or balcony, for a particular performance where unsold seats or uncalled for reservations become useless items;
2. Hotel rooms, either a suite, double, twin or single,

where rooms unoccupied on a given day represent wastage;

3. Plane or train tickets, roomette, sleeper, or seat on on train and first or tourist class on a plane where an empty seat on a particular trip becomes obsolete;
4. Automobile rentals, for compact, intermediate, full size or luxury type cars, for a particular time period, where unused cars represent lost rentals.

An application, analagous to double-crossmatching, would involve double-reservation for the more frequently demanded items with the assurance that all demands can be satisfied. An example of this principle, in practice, would be reserving more compact cars than available, while having larger models in reserve to satisfy excess demand for automobiles.

An application, analagous to the use of Rh negative blood for Rh positive patients, would be to use the items for a selected class of people with a higher demand rate but with a reduced return on the items than from regular customers. An example of this would be to make empty seats available at a reduced price basis to selected groups some time before their use, when insufficient regular customers were available to prevent their "waste".

An analogy to the recognition of a special class of patients occurs in retail selling of perishable food. The principle of

stock replenishment by which the oldest units are put in front and the fresher units in the back results in an increased probability that the older units will be used. The effect of making an item available to more customers is similar to assigning a unit of blood to a patient with a higher probability of usage.

The author would like to thank Dr. H. Stein and Professor L. Rosenberg for their assistance in the mathematical derivations of the maximum likelihood estimates. In addition, the work of Mr. F. Aronson and Mr. D. Wolfe was invaluable in assisting in the preparation of this report for final typing.

Special acknowledgement should also be made for the sincere assistance given the author by Professor D. Valinsky. His helpful encouragement throughout the course of this study is most deeply appreciated. Without it, this dissertation could not have been completed.

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CHAPTER I

INTRODUCTION

A hospital blood bank performs several functions in the hospital setting. Among the more important of these are the procurement, stocking and disbursement of blood for the hospital's patients. Thus, a blood bank may be considered as an inventory facility and will be regarded as one in this study.

The Blood Bank Inventory Problem

Blood products and blood type classification

Several blood products and blood components are available from a hospital blood bank. Blood products include packed red cells, washed red cells, and whole blood. Components include fibrinogen, platelets, factor VIII, bank plasma, fresh frozen plasma and 5% plasma protein. This study is not concerned with the blood components because they are not subject to the same procedures as the blood products. In addition, washed red cells have been excluded since this product must be used within a short time of washing and therefore cannot be returned to inventory if it is not transfused to the patient for whom it was originally intended. This study is therefore restricted to the activities of a hospital blood bank as an inventory facility for whole blood and packed red cells. Packed red cells are produced by rapidly removing the plasma from whole blood, and have the same expiration time.

Moreover, for the purpose of this report, a unit of whole blood and a unit of packed red cells will be considered interchangeable from both a supply and demand point of view and will be identified as a "unit" of blood.

Even within this framework, human blood cannot be considered a single product. Blood is considered to be one of four basic types, designated A, B, O, and AB according to the presence or absence of certain antigens in the red blood cells and certain agglutinens in the blood serum. In addition, each of the four types is subdivided into two groups according to the presence or absence of the Rh factor, thus creating a total of eight classes in the currently used blood classification system as illustrated in the table below:

TABLE 1
THE EIGHT MAJOR BLOOD CLASSES

Blood Group	Antigen	Agglutinen	Rh Factor
A+	A	Anti-B	Present
A-	A	Anti-B	Absent
B+	B	Anti-A	Present
B-	B	Anti-A	Absent
O+	None	Anti-A & Anti-B	Present
O-	None	Anti-A & Anti-B	Absent
AB+	A and B	None	Present
AB-	A and B	None	Absent

Source: J.P. Sonnendecker, and D.W. Millard, Industrial Engineering Analyses of a Hospital Blood Laboratory, Engineering Experiment Station Bulletin 180, Ohio State University, March, 1960, page 4.

Thus, a hospital blood bank is an inventory facility for eight products which for the most part may be considered non-interchangeable.¹ While any individual may have many other factors present in his blood, the above system is used to classify all individuals into one of the eight groups. The detection of all factors present in blood would be too time consuming and expensive. The reason for the blood classification is to prevent a person with a particular type of agglutinen (clotting factor) from being transfused with blood which contains the corresponding antigen and therefore would cause the donor blood to agglutinate upon transfusion, possibly causing the death of the recipient.

The need to consider eight products also brings about other problems, since each is not equally prevalent among all people. The following table will serve to illustrate the distribution of the eight blood types among all people:

¹This point will be considered later in this chapter.

TABLE 2
PREVALENCE OF THE EIGHT
MAJOR BLOOD CLASSES

Blood Group	Rh Factor	Observed Occurrence ^a	Expected Incidence of Occurrence ^b
A	+	34%	32%
A	-	4	6
B	+	14	12
B	-	2	2
O	+	36	37
O	-	4	6
AB	+	5	4
AB	-	<u>1</u>	<u>1</u>
All People		100%	100%

^aObserved incidence in data collected for a three-month period at Mount Sinai Hospital.

^bCalculated on the basis of blood group figures given in Maxwell M. Wintrobe, Clinical Hematology (Philadelphia: Lea and Febiger., 1961), p. 346, and Rh Factor breakdown in Byrd S. Leavell and Oscar A. Thorup, Fundamentals of Clinical Hematology (Philadelphia: W.B. Saunder Company, 1966), p. 517.

Thus some blood classes (e.g. A+, O+) are quite prevalent and some (e.g. B-, AB-) are quite rare. The existence of these "rare" blood types and the problems incurred in maintaining inventories of them are also discussed in this report.

Crossmatching and reservation

The existence of eight "products" does not by itself create a major inventory problem. Many industrial inventories consist of hundreds or even thousands of different items. It

is not the blood group and Rh factor that make blood different from any industrial item but the presence of the myriad other factors that are inherent in blood or have accumulated in blood during a lifetime through exposure to environment. People who have the same blood group (e.g. O) and the same Rh factor (e.g. positive) may have blood which is incompatible. If one of these person's blood were to be transfused into another it might cause a severe reaction in the recipient, possibly endangering his life. It is because of this possible incompatibility and the infeasibility of identifying all the factors in blood that a compatibility test must be performed between a possible donor and recipient, both of whom have blood of the same group and Rh factor. This compatibility procedure, called "crossmatching", does not identify any of the other factors in the donor's or recipient's blood. Its purpose is to verify that factors in the donor's blood are not incompatible with factors in the recipient's blood, that a reaction will not occur if the transfusion is performed.² Thus, to some extent, each unit of blood in inventory can be viewed as distinct from each other unit and must be crossmatched before it can be transfused.

The need to crossmatch each unit of blood before it can be transfused means that a request for a unit of blood for a

²The Mount Sinai Hospital uses a crossmatching procedure consisting of three tests; the Saline, Enzyme and Coombs tests. No combination of tests can guarantee against all possible incompatibilities but it is considered medically acceptable to proceed if all three of these tests yield negative (not incompatible) results.

patient must be made some period of time (usually 24 hours) before the blood is actually required by the physician. This is necessary in order for the blood bank to have sufficient time to perform the three compatibility tests.³ Once a unit of blood has been determined to be compatible with that of a patient, it is considered to be "reserved" for that patient. This status means that it is only available for the patient it was crossmatched against for the duration of the reservation. A reservation at Mount Sinai Hospital lasts for a maximum of 48 hours unless the physician requests an extension. If the patient's physician does not requisition the unit(s) he has on reserve before the reservation time elapses, the reservation is cancelled and the unit of blood is said to be "taken off reserve". This unit again becomes available for other patients' requests. Experience at Mount Sinai Hospital shows that about 50 percent of the units of crossmatched blood are taken off reserve, i.e. are not requisitioned by the physician.⁴ This can probably be attributed mainly to the general practice of physicians who order blood for a patient if there is any possibility of its being required. In addition, almost one-third of the units that are requisitioned by the doctors and

³ In emergency situations, the blood bank will issue blood of the same type as the patient's, crossmatched only by the saline technique. The other tests will then be performed and reported to the requesting physician.

⁴ J.B. Jennings reported 45 percent in his study at Massachusetts General Hospital in 1966. ("Hospital Blood Bank Whole Blood Inventory Control," Technical Report No. 27, Operations Research Center, Massachusetts Institute of Technology, December, 1967, p. 43.)

issued for their use are not transfused and are returned to the blood bank. Therefore, slightly more than one-third of the original requests for crossmatching result in the use (infusion) of the crossmatched unit. As the ordering practice of physicians is primarily a medical decision, it has been considered beyond the scope of this study except that the practices observed in the data that were collected are assumed to be representative and therefore must be considered as part of any inventory policy.

Effect of the reservation system

The process of crossmatching, reservation and either reservation cancellation or return of requisitioned blood, requires several days before a unit of blood becomes available for crossmatching for another patient. If the reservation is cancelled, this cancellation will take place at 8:00 A.M. on the first morning that occurs after 24 hours have elapsed. This policy will be followed unless the physician has notified the blood bank earlier that the unit will not be needed or has requested an extension of the reservation. In about 80 percent of the cases, this practice results in a reservation duration of two calendar days. For example, a unit crossmatched on April 10 and not requisitioned will be released April 12.

If a unit is requisitioned and is not needed, it will be returned to the blood bank, usually later in the same day. If the blood was stored properly (refrigerated at 5°C), then the hospital blood bank will accept its return. However, the blood bank

will keep the unit on hand for 24 hours before re-using to check for effects of improper storage, unless it is positive it was properly maintained, as in a surgical refrigerator.

With most non-perishable products, delays in use are important only in their effect on inventory carrying costs. However, blood is a perishable commodity. The red blood cells lose their viability when removed from the human body. If the process goes too far there will not be enough viable red cells remaining in the blood to serve its life-sustaining functions. In current practice, blood is stored mixed with an ACD solution (tri-sodium citrate, citric acid, dextrose and water)⁵ and refrigerated at 5°C. When stored in this manner, at least 70 percent of the red cells maintain viability for 21 days. A 21 day period (from the time of donation) is the presently accepted standard in most hospitals during which blood may be transfused. After this period, blood is no longer acceptable for transfusion, although some of its components may still be extracted or the unit might be used in research.

Repeated crossmatching of a unit of blood resulting in either a reservation cancellation or a return would cause that blood to go "out of date" and therefore be wasted. Waste of such a "precious" commodity as blood is one of the major reasons for this study.

⁵A new preservative solution (CPD) is currently being introduced in many blood banks, because of its improved ability to preserve red blood cells.

Variability in demand and supply of blood

In addition, it must be remembered that the demand on the hospital blood bank is not constant but variable in nature and is not precisely predictable.⁶ Both the number of patients who request blood as well as the number of units requested for each patient are subject to considerable variability. If there are only a few requests for blood of a particular type, some of the units of that type will get one day older and one day closer to being wasted, simply waiting in inventory.

Up to this point, only the problems of a blood bank resulting from the nature of the product and the nature of the demands for it have been discussed. If the blood bank is to supply blood to patients in the hospital it must obtain that blood. The hospital's blood supply is obtained in a variety of ways. Most of the hospital's supply is obtained from a central agency such as the Greater New York Blood Program and through a variety of commercial blood banks. Blood may also be obtained through patient participation in a group blood plan as well as through individual donations. Less than 15 percent of the blood received by the Mount Sinai blood bank comes from individual donations at the hospital. The remaining blood is therefore obtained from the various agencies and commercial sources best able to meet the requirements of the hospital. This blood is usually obtained several

⁶Blood needs for certain uses such as open heart surgery are scheduled well in advance and therefore specially supplied and excluded from the study.

days after it was donated and in some cases it may be as much as 14 days old when received by the hospital blood bank. Since blood has a total life of 21 days, the blood bank of a hospital may find that a good part of that life has elapsed before the unit is received into inventory.

Summary

A hospital blood bank can be viewed as an inventory system with stochastic demands by patients and with stock replenishment from various sources of blood. In addition, some of the characteristics of blood banking make it very different from the typical industrial inventory problem. Special characteristics of these problems are summarized below:

1. Blood deteriorates with age. If it is not used within 21 days from the date it was drawn it becomes unacceptable for transfusion purposes. This raises the problem of the age of inventory and the "obsolescence" or "out-dating" of the units in inventory;
2. A request for blood cannot be filled with any unit of the same group and Rh type. A crossmatching must first be made to insure compatibility. This crossmatching and the consequent reservation of the crossmatched blood causes blood to be held and age in reserved inventory for one patient, and then perhaps not even be used, when it might have been used for some other patient;

3. Requests for blood do not come into the blood bank at a constant rate. The requests are stochastic in nature and cannot be predicted exactly on a day-to-day basis. Moreover, a request does not necessarily result in the use of a unit of blood. When a requisition does not follow the request within a specified period of time the reservation is cancelled and the older blood is returned to the regular inventory. Even if the blood is requisitioned, the doctor may have reserved more than is eventually transfused and thus some of the now older blood returns to inventory;
4. Because the great majority of the hospital's blood supply must be obtained from outside sources, the hospital has no real control over the age of the blood that it receives into inventory. If the blood had been drawn 5 days before it arrived at the hospital, then the blood bank has the ability to use that unit of blood for only 16 days of its 21-day life.

Criteria for Evaluating Inventory Policies

The most important purpose of the hospital blood bank is to maintain an adequate supply of blood. To satisfy patient demands, quantities of blood of each of the eight types are kept on hand in the hospital blood bank. The maintenance of a supply of blood in combination with the fact that many reservations are never called for and many units which are requisitioned are returned to

inventory results in some of the units of blood in inventory going "out-of-date". Some of these units still can be used, at greatly diminished value, by extracting the plasma, or in research. However, these units have much less utility than blood available for transfusions. Blood which goes out of date will be considered waste and is one of the penalties associated with the maintenance of an inventory.

Because the demand for blood is stochastic in nature, and subject to variation both in number of patients and in the amounts of blood needed for each patient, there is always the possibility that more blood will be requested than is available in inventory. In most inventory systems, when demand is greater than supply on hand a "stock-out" results creating some unsatisfied demand. In a blood bank, because of the function of the blood, it is considered absolutely imperative to fill every request for blood. Stock-outs are not permitted to occur, and demands which would have resulted in shortages cause the blood bank to implement special procedures to correct the anticipated deficiency. There are two possible actions that the blood bank may take:

1. "Walking Blood Bank". A walking blood bank is composed of people, mainly hospital employees, whose blood types are known and who have agreed to donate blood when called upon by the blood bank. The walking blood bank is mainly used when fresh blood is needed, in emergency situations, or when a rare blood type is needed and cannot be obtained from other sources.
2. Special calls to the various blood collecting agencies.

Most orders for blood for stock replenishment are placed early in the morning. However, if the blood bank finds itself in need of certain types of blood sometime later in the day, the bank will call the nearest agencies requesting the blood on an emergency service basis. The hospital will take the blood from the agency that can supply it in the shortest time, usually less than two or three hours.

While these actions result in a considerable disruption of the blood bank routine and a concomitant cost associated with the special ordering and receiving of this blood, this penalty is obviously of far less moment than not being able to supply the blood to the patient.

There are other "costs" associated with the maintenance of a blood bank besides that of wastage and shortage. Some of these such as storage costs, ordering costs, and carrying costs, are so negligible when compared with wasting blood or incurring a shortage that they can be excluded from consideration without fear of distorting the problem. Other costs associated with the operation of a blood bank, such as typing and standard crossmatching are virtually unaffected by changes in the inventory policies and they have also been excluded from consideration. Still other costs, such as the effect of the hospital's operations on the community's blood supply may be considered to be part of the cost associated with wastage or shortage as the case may be.

Two other factors are worth mentioning at this point. One

is the age of the transfused blood. For certain purposes, blood which is less than three days old is necessary and, in general, younger blood is preferred by physicians so that the age of the transfused blood has been considered by some researchers as one of the most important considerations in blood bank inventory policies. While recognizing that younger blood is preferred, for the purpose of this study, the crucial difference in value occurs when a unit of blood becomes too old for transfusion and all blood that is acceptable for transfusion is therefore considered of equal value. Of course, if two policies yield equivalent results for all other major considerations, then if one yields lower ages of blood at transfusion than the other, it would be preferred.

The other factor has to do with operating costs of the blood bank. Most of these are negligibly affected by changes in inventory policies and they have been excluded from consideration. However, this study will make a major investigation into a change in inventory policy that will result in significantly increased operating costs. Therefore, the evaluation of this policy will have to relate increased operating costs to changes in blood wastage levels and/or blood shortage occurrences.

Alternative Policies in Blood Bank Inventory Control

Previous research on blood bank inventory control policies has centered on the "optimal inventory level" problem. This research dealt with the number of units of a particular blood type that should be kept on hand in order to maintain a "proper"

balance between the amount of out-of-date blood (wastages) and the amount of special orders (shortages) that occur at that desired inventory level. While some work on inventory levels was done in this study, it was used primarily to validate the model of a hospital blood bank created for use in this study. The results of this work also served as a basis for evaluating the effects of the alternative policies that are the main purpose of this investigation.

Three particular policies will be presented in detail in this study. A brief discussion of each of these areas is given below:

1. Two of the major contributors to blood aging in inventory and going out of date are: (a) the requirement that each unit be crossmatched against the requesting patient before transfusion, and (b) the ordering policy of doctors which is conservative, resulting in many orders for blood which are never actually requisitioned. Since units are reserved, they are therefore not available to any other patient until the reservation period expires. The safety requirements which necessitate a crossmatch are not subject to question. Neither are the medical judgments of physicians who are considering the well being of their patients. Thus, the above two problems cannot be ignored, but must be considered as part of hospital blood banking.

The approach being investigated here makes a unit of

blood available to two patients. It crossmatches a unit in inventory against two requesting patients, so that while it is on reserve it is available to either of the patients. Thus, if one of the requesting patients turns out not to need the blood it is still available to the other. This procedure is called "double-crossmatching" in this report. The crucial point is that the method, as proposed, does not introduce the possibility of failure in having a unit available (i.e. crossmatched and reserved) for the second patient, even if the first patient uses the unit of blood which was on reserve for both of them. It is believed that this method of crossmatching can greatly improve the chances that a unit of blood will actually be requisitioned for transfusion because it can be available to two patients. Complete details of the theoretical and operational bases of this system are presented later in this report.

2. As a unit of blood becomes older it has less and less chance to be transfused. If there were some patients whose actual needs for blood were much closer to their request levels than the hospital population in general, a request for blood for this type of patient would much more frequently result in a requisition and transfusion. If this information were available to the blood bank, it might be of great help in making

proper use of blood which otherwise might have gone out-of-date. A statistical analysis of blood ordering and utilization at the Mount Sinai Hospital revealed the existence of such a class of patients. A procedure for filling requests for blood using this information was devised and investigated in this study.

3. The problem of maintaining an adequate inventory of blood is complicated by the fact that some of the blood types are much rarer and therefore much less demanded than other types. In order to maintain protection against shortages of these rarer blood types, the blood bank must still maintain a sufficient inventory even though the average demand may be low. These low demand levels for the scarcer Rh negative blood types result in much higher wastage of blood than the more "common" types. In addition, the "fear" of running out of these blood types because of their difficulty to procure on an emergency basis may result in higher stockage and even greater wastages. While it is not possible to transfuse Rh positive blood to Rh negative patients,⁷ there is no medical

⁷There are special conditions under which Rh positive blood may be used for Rh negative patients. These are:

- "1. Rh-negative males who have not been previously transfused,
2. Rh-negative females who have had a hysterectomy and who have not been transfused or been pregnant,
3. Rh-negative women who have passed the age of menopause and who have not been pregnant or transfused."

from K.S. Ranganathan, "Essentials of Blood Grouping and Clinical Applications," Grune and Stratton, Inc., 1967.

reason that Rh negative blood cannot be used for Rh positive patients. This practice is simply not employed in order to conserve the rarer negative blood for patients who must have it. However, the question arises as to whether it would be desirable to try to use Rh negative blood for an Rh positive patient if the negative blood only had a short period of usable life remaining, and there was no demand for a negative unit from an Rh negative patient.

A procedure was developed which permits the cross-matching and transfusion of Rh negative blood to Rh positive patients of the same blood group under two conditions: (1) when the negative blood exceeds some predetermined age; and (2) there was no negative patient who needed blood. This procedure was investigated to determine its effect on the wastage of negative blood, its effect on the supply of negative blood and its impact on Rh positive wastage.

Method of Investigation

A computer simulation model of a hospital blood bank was used to investigate the alternative policies stated in the previous section. The simulation approach involves the creation of a model or representation of the system or area being investigated so that the model may be used to "test out" various policies without upsetting the actual operations of the system if any of the

new policies were actually detrimental.

The simulation model was used rather than an analytical or mathematical model of the system because of the difficulty of representing all facets of the blood bank system in a single model. Analytical models used in previous research have simplified the representation of the system to the point that they fail to reflect the true character of the system.⁸ Some analytic models have omitted such basic characteristics as the need for cross-match and reservations, the return of blood which was removed from the blood bank, and the complex nature of the demand in which many requests never become requisitions. Simulation models currently available do not permit any investigation of the three proposals previously set forth.

A highly detailed simulation model of a hospital blood bank was therefore created and programmed to be run on the IBM 360 Model 40 computer. The simulation was written using FORTRAN level F and will run on any IBM 360 with a 128 K memory.⁹ The simulation model was made sufficiently general to permit investigation of proposed procedural changes while still fulfilling all mandatory functions of a hospital blood bank inventory system. This simulation model includes many considerations which were never included in previous models because a less complete representation was sufficient to answer the types of questions that

⁸A detailed discussion of previous research in blood bank inventory control is provided in Chapter III.

⁹A listing of the computer program is provided in Appendix V.

were raised by the researcher. Some of these considerations are:

1. Inclusion of all eight major blood categories in order to: (a) measure impact of demand levels and characteristics on the effectiveness of the proposed changes, especially double-crossmatching; (b) avoid the assumption of independence of blood type and allow the investigation of possible Rh negative blood use for Rh positive patients in certain special circumstances.
2. Explicit identification of each patient and his demand, i.e., total demand is obtained by generating the number of patients requesting blood each day and then determining the number of units of blood desired by each patient, rather than by generating the total number of units desired each day. The identification of each patient is necessary in order to investigate: (a) the concept of double-crossmatching. For double-crossmatching to be meaningful it is necessary to crossmatch a unit against requests from two different patients; and (b) the identification of patient categories with demand and usage patterns different from the general patient population which may be utilized for the benefit of the blood bank.
3. To prevent distortion of the system through oversimplification, the inventory functions implicit in all hospital blood bank systems are explicitly included

in the model. These embody such considerations as:

- a) Ordering blood from local blood centers when its inventory is not at the desired level.
- b) Receiving donated blood at the hospital.
- c) Receiving patients' requests for blood.
- d) Crossmatching each of the requests and reserving units of blood for patients.
- e) Acknowledging requisitions for reserved blood and filling them.
- f) Receiving back into inventory those units which were called for but not transfused and returned to the blood bank.
- g) Receiving blood which was ordered and processing the units into inventory.
- h) Cancelling the reservations of those units which were crossmatched and thus reserved but were not requisitioned and whose reservation period has elapsed.
- i) Removing from inventory any units which have exceeded the allowable age for transfusion.
- j) Initiating special orders for blood when and if the blood bank is in danger of not having sufficient blood to satisfy the demand.

In addition, the computer model maintains records of expirations, shortages, age of blood on transfusion, number of crossmatches performed as well as information

on reservations, call fors, and returns, to evaluate the effectiveness of a particular set of operating policies.

Data Collection

To put the simulation model previously described into operation, an extensive amount of information had to be collected on the operation of the blood bank system. Most of the information that is necessary for the model pertains either to the nature of the blood supply that is used to replenish its inventory or to the nature of the demand which the inventory must serve.

To obtain this information, complete data were collected for a three-month period on the operations of the blood bank at Mount Sinai Hospital. These data were then analyzed to obtain the input data which are required for the operation of the simulation model.¹⁰

The input consists of parameters of statistical models which describe the observed process, when such models could be found. When appropriate models could not be constructed, actual empirical data were used as experience curves to represent the appropriate probabilistic process.

The data used as input for the simulation model include:¹¹

¹⁰Detailed discussion of available hospital data, their collection, verification and analysis are presented in Appendices I, II and III to this report.

¹¹Detailed instructions on the simulator input requirements are given in Appendix VII.

1. The distribution of the age of blood ordered from outside blood sources;
2. The distribution of the number of donors per day by blood type;
3. The distribution of the number of patients requesting blood per day by blood type;
4. The distribution of the number of units requested per patient by blood type;
5. The distribution of the number of days elapsed between the date of the request and the date of the crossmatch and reservation by blood type;
6. The distribution of the number of units of blood requisitioned (called for) conditional on the number of units of blood requested;
7. The distribution of the elapsed time between the date of the crossmatch and the date the blood was actually requisitioned by blood type;
8. The distribution of the number of units of blood returned to inventory conditional on the number of units of blood called for;
9. The distribution of the elapsed time between the date the unit was called for and the date it was returned;
10. The distribution of the elapsed time between the date a unit was crossmatched and the date the reservation expired (taken off reserve) if the unit was not called for. The number taken off reserve is the difference between the number requested and the number called for.

A detailed description of data collection, analysis, the statistical distributions and their parameters used in the simulation model is presented later in this report.

CHAPTER II

DETAILED OPERATION OF A HOSPITAL BLOOD BANK

To fully appreciate the inventory problem in a hospital blood bank, it is necessary to understand its day-to-day operations.¹ This section is intended to facilitate discussion of the simulation model and previous research. Although the operation described here is based on that of the Mount Sinai Hospital Blood Bank, the major characteristics are identical with most hospital blood banks with only detailed procedures differing from one another.

Inventory Replenishment

Only a small portion of the blood required at Mount Sinai Hospital is obtained directly from donors. Most of it is obtained from central banks, such as the Greater New York Blood Program, or from commercial banks, such as Pfizer Diagnostics or Pioneer Blood Bank. Periodically, usually each morning, the chief technician examines the inventory status of each of the blood types and determines how many additional units of each type are necessary to bring the inventory up to its desired level. Phone calls are then placed to the central and commercial banks, in order of preference, to order the desired blood. In many cases the order is

¹The operations discussed in this section are only those which relate to the inventory maintenance function of the blood bank and do not include any of the testing and diagnostic functions also performed.

sequentially placed with several sources before it is complete.

These orders arrive at the hospital blood bank in the afternoon of the day they were ordered. They are placed in a separate storage facility until they are screened and re-typed by the technicians at the hospital. Each unit is then tagged with a donor number for identification and is entered into regular or unreserved inventory so that they are usually ready by late evening and available for the next day's orders.

If, during the day, it appears that the hospital bank has become seriously low in its supply of a particular blood type, the previous procedure for readying blood for inventory could be accelerated for those units which were in short supply. In addition, if more units were required during the day, an "emergency" ordering procedure is in effect with the hospital's regular sources, by which it can obtain special orders in from one-half to two hours. The hospital also operates a walking blood bank, made up mainly of hospital employees, primarily to obtain fresh blood when needed. This source could also be used to obtain needed blood in an emergency situation.

Disbursement of Blood

Requests for crossmatch and reservation

All orders for blood begin with a request for crossmatching and reservation of a unit of blood. Since a patient cannot be transfused with a unit of blood unless it has first been cross-matched against his blood, this request is forwarded to the blood

bank by the patient's physician. A separate request has to be made for each unit of blood desired. Unless previously determined, the request is accompanied by a sample of the patient's blood for typing and grouping. After the patient's blood type and group have been determined, the request is sent to the crossmatching area to obtain a compatible unit of blood. Three compatibility tests (Saline, Enzyme and Coombs) are performed and if the tests all yield negative results, the crossmatching is acceptable. The inventory reference for that unit of blood is then removed from the regular inventory file and is placed in the reserved inventory list, together with information identifying the patient for whom it was reserved. The date that the reservation will expire is stamped on the request slip. At Mount Sinai Hospital this is two days from the day of the crossmatch and reservation for regular orders and one day for emergency and urgent orders unless the physician requests the reservation be extended, which happens infrequently.

Requisition of reserved blood

When the physician needs the units of blood he has reserved, he sends a "Request for Blood Components" to the blood bank. Up to three units of blood may be requested for a patient per form if previously reserved. At the blood bank, the units which have been reserved for that patient are located starting with the oldest one, since the doctor may not have requested all those on reserve. The unit numbers are written on the request slip

and the requested quantity is sent by messenger to the appropriate location. If the requisition originates in the operating room area, the blood bank fills in the blood unit numbers upon telephone request and sends the partially completed "call for" slip with the units of blood to the operating room, where the slip is completed with the patient's identification and is returned to the blood bank. The unit identification tag is split in half; part goes with the unit and the other part is attached to the requisition slip.

Return of requisitioned blood

Units of blood which were requisitioned but not transfused may be returned to the blood bank if they have been properly stored. The operating room area, in particular, has refrigerators which are used for the storage of blood requisitioned but not needed for the day's surgery. The units in these refrigerators are returned to the blood bank at specified intervals. If there is any doubt about the condition of the blood, it is set aside for 24 hours and then tested to see if it is still usable.

When blood is returned, the references to that unit have to be recreated. The reservation for the patient who has returned the unit is discarded, unless the physician has asked that it still be maintained, which is rare. This new identification tag for the unit is placed in the appropriate place in the unreserved list so that the unit is again available for another patient.

Cancellation of reservation

Early each morning, the chief technician examines the list of units remaining on reserve. If the date stamped on the original request for crossmatch and reservation indicates that the reservation has expired, then the reservation is cancelled. The patient's identification is removed from the blood unit's tag and the tag is taken off the reserved list and returned to the unreserved inventory file. Many of the reservations are never actually requisitioned and are therefore cancelled when they expire, greatly increasing the supply of available blood while not changing the physical quantity on hand.

Expiration of life

Preserved blood, properly stored, can only be used for transfusion within 21 days of the day it was drawn. Blood older than 21 days is unacceptable for use in transfusions. Therefore, at the beginning of each day, the complete inventory of blood is checked and any units that have exceeded their permissible life are removed from inventory and are no longer available to patients. Some of these units may have the plasma spun off for use at the hospital or may be used in research. The rest are usually returned to the central sources for their use. The value of blood so used is minor compared with its value in transfusions and therefore any blood that goes "out-of-date" can be considered to be wasted.

Blood Flow in a Hospital Blood Bank

The inventory system can be schematically represented as a blood flow process. The following figure illustrates that flow, showing:

1. The inputs of blood into the system, from donors and central sources;
2. The processing of the blood units in response to physicians' actions;
3. The departure of blood from the system through transfusions and expirations.

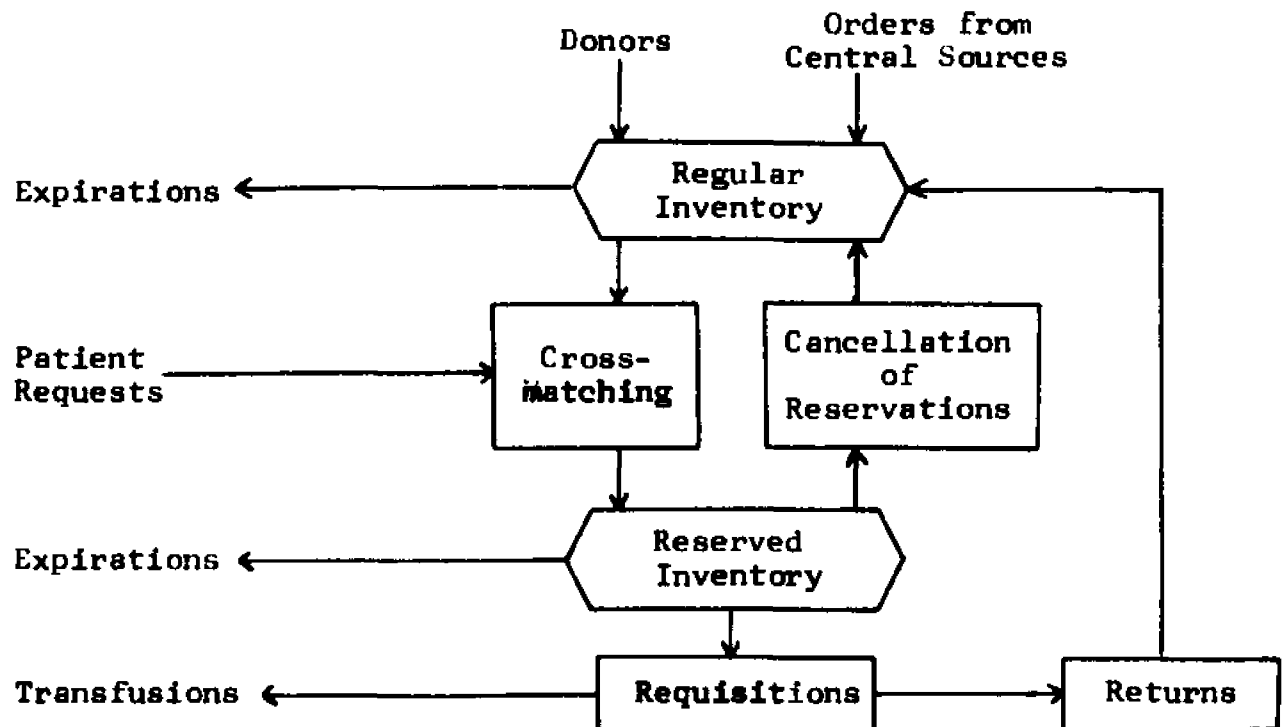


Fig. 1.--Description of inventory system as a blood flow process.

CHAPTER III

PREVIOUS WORK IN THE AREA OF BLOOD BANK INVENTORY CONTROL

Hospital blood bank inventory control has attracted the attention of several researchers. The original major work in the field was done by J. P. Sonnendecker and D. W. Millard in 1960. Sonnendecker was concerned with day-to-day forecasting of the order size while Millard's approach involved the application of industrial inventory models to the blood bank system. R. C. Elston and J. C. Pickrel, in 1963, were able to relax some of the restrictions of the previous mathematical models by using a simulation model of a blood bank. A. Silver and A. M. Silver and E. L. Hurlburt and A. R. Jones followed, in 1964, with empirical or heuristic methods for establishing inventory levels. J. B. Jennings, in 1967, provided a major advance in the field by including the reservation concept in his simulation model. In 1969, C. C. Pegels developed a model which might be applicable to central blood banks and, in the same year, in collaboration with A. D. Jelmert, created an analytical model based on Markov chains which also included the reservation concept.

These activities are summarized and discussed in the following sections of this chapter.

Research with a Single Inventory System

Sonnendecker¹

The objective of this research was to develop a model for use in forecasting the daily requirements of blood and to determine how much blood to order from the central source. The basic forecasting model developed is:

$$O_{it} = d_{it} + w_{it} - b_{it} - p_{it} - I_{a_{it}} + I_{d_{it}}$$

where

O_{it} = the number of units of type i to be ordered from the outside source for the next day.

d_{it} = estimated demand for type i blood for the next day.

w_{it} = amount of type i blood estimated to be wasted during the day.

b_{it} = amount of type i blood estimated to be received from other sources, such as donors, during the day.

p_{it} = amount of type i blood that it is estimated will be called for during the day.

$I_{a_{it}}$ = amount of type i blood in unreserved inventory at the beginning of the day.

$I_{d_{it}}$ = desired amount of type i blood on hand in unreserved inventory during the day to meet non-routine or emergency demand.

The model is not designed to investigate changes in inventory policies nor determine their effect on the shortages and

¹ J. P. Sonnendecker, "A Model for Forecasting Whole Blood Requirements of a Hospital Blood Laboratory," Industrial Engineering Analysis of a Hospital Blood Laboratory, Engineering Experiment

wastage incurred under those conditions. Moreover, an acceptable wastage level is included as an input to the model. In addition, by using the estimated demands, estimated receipts from other sources, and estimated number of call for as input to the model, a probability of shortage is implied. The only decision that the model is concerned with is the amount to be ordered each day. It does not consider any other changes in the operating policies of the blood bank. Although the model seems to be feasible for its intent, Sonnendecker indicated that problems may be encountered in its implementation because of the difficulty in having hospital personnel use the required statistical techniques and the general unavailability of data in convenient form for use in the model.

Millard²

The approach taken in this research was to determine if simple inventory models, developed in industrial applications, could be applied to the blood banking situation. He starts with a classic queuing model with Poisson arrivals which are entries into inventory and exponential service rate which are demands for blood. This random demand model is improved by introducing periodic

Station Bulletin 180, Ohio State University, Columbus, 1960.

²D. W. Millard, "Industrial Inventory Models as Applied to the Problem of Inventorying Whole Blood," Industrial Engineering Analysis of a Hospital Blood Laboratory, Engineering Experiment Station Bulletin 180, Ohio State University, Columbus, 1960.

inputs into inventory such as receipts from outside sources. He first considers a model with no lead time, that is with no time interval between placement of an order and the arrival of the blood; then he develops a model with a time lag between order placement and order receipt. He also discusses the generalization of the periodic input model to the case where part of the input is random such as donations and part is periodic, from outside sources. The latter models assume that demand which results in stockouts will be filled on backorder when the next batch of inventory arrives, which is unrealistic in blood banking. The only inventory policy variable under consideration by Millard is the desired or maximum inventory level which determines the order size. He reports a sample application of the model and gives the probability of a shortage and the probability of blood expiring at various levels of maximum inventory. The results for blood expiration at "low" probabilities of shortage are far lower than would be expected. In addition, the overall results for blood expirations seem to be quite insensitive to the maximum inventory level. The atypical results probably ensue because Millard's models do not consider the necessity of a crossmatching and reservation procedure in a blood bank.

Elston and Pickrel³

Elston and Pickrel created a simulator to relax some of the oversimplifying assumptions of previous research. The purpose of their research was also to study the effect of varying inventory and activity levels on the amount of shortages and out of date blood incurred using a particular set of conditions. Their model is basically similar to the previous models in that it has only a single inventory for each blood type. This inventory is supplied by donors and by orders from a central source and depleted by transfusions and wastage. The model does not include the effects of a reservation system, and the authors point out this is a possible cause of discrepancies between the predicted and actual operating statistics for the blood bank which was studied. As before, the only aspect of inventory operating policy considered to be controllable is the desired inventory level.

Silver and Silver⁴

The authors describe an empirical method of setting inventory levels in order to minimize the sum of shortages and wastage costs. This method makes use of previous occurrences of unusual

³R. C. Elston and J. C. Pickrel, "A Statistical Approach to Ordering and Usage Policies for a Hospital Blood Bank," Transfusion, Volume 3, p. 41, 1963.

⁴A. Silver and A. M. Silver, "An Empirical Inventory Control System for Hospital Blood Banks," Hospitals, Vol. 38, p. 56, August 1, 1964.

usage levels over semi-monthly periods. The concept involved is basically a simplified version of the single inventory models discussed above.

Hurlburt and Jones⁵

This paper presents a discussion of the effects of three major factors on the control of a blood bank's inventory. The input of blood into inventory, the requests for blood, whether used or not, and different usage rates and timing are discussed relative to their effect on the amount of wastage that occurs. Heuristic rules are presented for the determination of required inputs based on average daily usage. These rules result from the consideration of an implicit model similar to the ones discussed above, simplified to a deterministic version by treating average daily usage as if it were constant. Since the rule is based on constant demand it does not consider shortages. The paper states that after the rule has been applied, a "reasonable" inventory level can be selected to balance shortages against wastage. The desired inventory level is the only variable considered for control.

Pegels⁶

Pegels develops various models for determining the desired

⁵E. L. Hurlburt and A. R. Jones, "Blood Bank Inventory Control," Transfusion, Vol. 4, p. 126, 1964.

⁶C. C. Pegels, "A Blood Bank Collection Scheduling and

number of units to be put in inventory, based on a specified probability of allowable shortage and a forecast distribution of demand. His models consider different assumptions of availability of information about demand and supply distributions, and the nature of statistical distributions used to describe the demand. These models do not consider blood wastage, assume all inputs of blood are to be freshly drawn, i.e., they are 0 days old, and include only one inventory for each blood type. On this basis, these models might be useful for planning the desired number of units to be drawn by central banks but they have very little application to the real problems of a hospital blood bank.

Research Allowing for a
Reserved Inventory

Jennings⁷

This comprehensive study presents a major advance over all previous work in this area. Jennings' model includes all factors necessary to investigate the inventory level problem in a hospital blood bank and was simulated in its full complexity rather than being simplified for possible analytical solution.

Inventory Control System," AIEE Transactions Industrial Engineering Research and Development, Vol. 1, No. 1, p. 51, March 1969.

⁷ J. B. Jennings, Hospital Blood Bank Whole Blood Inventory Control, Technical Report No. 27, Operations Research Center, Massachusetts Institute of Technology, December, 1967.

The model is the first that specifically considers the necessity of including the reservation system within itself and makes provision for both reserved and unreserved inventory status.

Included are both inputs from donors and inputs ordered from a central source. The model also recognizes that the age of the blood received from the central source is not deterministic.

The demand for reservation is a stochastic variable. The model, therefore, generates daily demand probabilistically. Provision is made for the fact that not all reservations are transfused by randomly assigning some to be used and some to be returned to unreserved inventory on the basis of Bernoulli trials.

Consideration is also made for the fact that blood which is reserved but not transfused spends some time on reserve and is unavailable until its reserve status is terminated. Moreover, this time is not necessarily constant for all units of blood reserved. Jennings generates the time when the blood is available using probability distributions conditional on the age of the blood.

Even though this model does represent hospital blood banking much more accurately than previous models it has some limitations. The desired inventory level is still considered to be the only controllable variable and the effect of changing this level was observed in both shortages and wastage generated by the simulator to obtain a valid evaluation of the effect of this one

parameter. Most of the other parameters Jennings studied were parameters of exogenous variables which are input to the simulator, such as the age of blood received from outside sources, rather than variables over which the hospital has control in its operation of the blood bank.

Some of the limitations of the Jennings model are:

1. His model can study only one blood type at a time.

This does not reduce its generality under the "reasonable" assumption of no cross-transfusion of a patient of one type with a unit of blood of another type. It is true that there is very little, if any, cross-transfusion done in hospitals today but allowing cross-transfusion under acceptable conditions is an important operating policy that should be investigated. In order to study such a policy it is necessary that the model include at least two blood types (positive and negative Rh factors for the same blood group) as well as a procedure for accomplishing the cross-reservation of a unit of blood when the specified conditions are met.

2. Jennings considers the stochastic nature of total demand for blood by using as input the distribution of the total number of units requested per day. The model does not generate patients and is not capable

of identifying specific patients. The total demand for units is all that is necessary if the one-to-one reservation system currently in use is not questioned. However, this type of demand generation does not allow any investigation of possible crossmatching systems which require patient identification. In order to accomplish investigations of this nature, it is necessary for a model first to generate randomly the number of patients each day. It must then generate the number of units requested for each of those patients to arrive at the total daily demand. Thus, each patient and his "order" is explicitly identified.

3. This model states that when blood is reserved it will either be transfused or be returned to unreserved inventory after some randomly generated elapsed time. It does not differentiate between units which are not called for and whose reservations are cancelled and units which are called for but are then returned. Nor does it differentiate between the two event sequences in the elapsed time until the unit is available again. Moreover, the time until the unit is available is generated from probability distributions which are conditional on the age of the blood. The timing of a

return should be independent of its age and the cancellation of reservations is determined by hospital policy rather than by the age of the blood except when the blood is about to go out of date.

4. Because the patients and their orders were not generated, the fact that patients requesting different quantities of blood have different probabilities of usage are not considered in this model. Such consideration is important as the order will probably be crossmatched as part of a batch using sequential, or almost sequential, units from unreserved inventory.
5. The model includes the ordering of blood from central sources and considers the probabilistic nature of the age distribution of blood received on the basis of these orders. However, the probabilistic age assignment has been simplified so that all units of blood received on the same day are assigned the same randomly generated age.

Pegels and Jelmert⁸

Two analytical models using the theory of absorbing Markov chains are presented in this paper. The first model has 21 states which represent the ages of the blood in days, plus two absorbing

⁸C. C. Pegels and A. D. Jelmert, An Evaluation of Blood Inventory Policies: A Markov Chain Application, State University of New York at Buffalo, School of Management, July, 1969.

states, transfusion and expiration. Each of the 21 age states has a probability, p_i , of blood being transfused and a probability, $1-p_i$, of blood reaching the next age state, except state 21 for which $1-p_{21}$ represents the probability of expiring, which is the probability of entering the second absorbing state. For a given set of p_i this formulation can be used to determine the probability of wastage, which is the probability of being absorbed in the expiration state, the average age at transfusion, which is the expected number of transitions until entering the transfusion absorbing state, and the average inventory level. However, this model has several limitations:

1. It does not make any distinction between regular and reserved inventory, which is necessary for the model to be a good representation of a hospital blood bank.
2. It assumes that all blood enters the system in the first state, that is, as fresh blood, which is unrealistic for a hospital blood bank.
3. Pegels and Jelmert define two types of blood issuing policies. A modified LIFO policy is defined as one in which fresher blood has a higher probability of being transfused than older blood ($p_i > p_{i+1}$ for $i = 1, 20$) and a modified FIFO policy is defined as one in which older blood has a higher probability of being

transfused than younger blood ($p_{i+1} > p_i$ for $i = 1, 20$). In fact the probability of a unit of blood being transfused is equal to the probability of being crossmatched times the probability of being transfused if it has been reserved. The probability of being transfused if it has been reserved is independent of age unless the blood bank is making use of some kind of special patient policy. The probability of being crossmatched while being a function of age is also dependent on the demand for blood each day, which doesn't explicitly appear in this model, as well as the number of units of blood with a higher priority of being crossmatched on that day. The crucial question of how to determine the conditional probabilities of transfusion for any meaningful inventory policy is not really resolved. Two methods are given by the authors which seem to involve circular reasoning. One assumes a desired probability of wastage and the other a desired average inventory level, both of which are outputs of the Markov transition model.

This model cannot be considered appropriate to a hospital blood bank because of the single inventory and fresh blood input assumptions. It might be applicable to a central blood source if

the p_i could be equated with the probability of the unit being requested by a hospital blood bank. Their second model is more representative of the real hospital situation because it includes the need for crossmatching and reservation in its formulation.

In this formulation, the life of the blood is divided into 11 two-day periods, in each of which the unit could be in the regular inventory or on reserve, resulting in 22 inventory states plus the two absorbing states of transfusion and expiration. In this model, a unit of blood can only be transfused once it has been reserved and, as before, can only expire after it has been in the last age state. If a unit is not reserved in period i then it can either be reserved in period $i+1$ or remain in regular inventory in period $i+1$. If a unit is on reserve in time period i , then it can either be transfused or it can remain on reserve in time period $i+1$, or it can be returned to the regular inventory in period $i+1$. Thus,

$$P(\text{reg}_i, \text{reg}_{i+1}) + P(\text{reg}_i, \text{res}_{i+1}) = 1.0$$

$$P(\text{reg}_{i+1}) = P(\text{reg}_i, \text{reg}_{i+1}) + P(\text{res}_i, \text{reg}_{i+1})$$

$$P(\text{res}_{i+1}) = P(\text{res}_i, \text{res}_{i+1}) + P(\text{reg}_i, \text{res}_{i+1})$$

$$P(\text{trans}_i) = 1.0 - P(\text{res}_i, \text{reg}_{i+1}) - P(\text{res}_i, \text{res}_{i+1})$$

A unit of blood that is not on reserve in the last time period must expire and those that are on reserve but not transfused will also expire. Thus,

$$P(\text{expire}) = P(\text{reg}_{11}) + [1.0 - P(\text{trans}_{11})]$$

This model can be used similarly to the first model to establish the probability of wastage, expected age on transfusion and average inventory level. Although the reservation process has been introduced into this model, the previous problems of the age of incoming blood and the establishment of the transfusion probabilities to reflect an actual inventory operating policy still remain.

Moreover, the Markovian assumptions which apply to transition probabilities are incompatible with the real blood banking situation. Specifically, the probability of a unit remaining on reserve from one period to the next is not only a function of whether the unit was on reserve in the previous period but if it was on reserve it will depend on how long it has been on reserve. These conditions violate the Markovian assumption that the transition probabilities be independent of the previous states through which the unit has passed in arriving at its current state. The effect of this failure in the assumptions is not known, but it raises doubt about the applicability of this model.

Summary

Early work in the area of hospital blood bank inventory control was inadequate because these inventory models failed to include any representation of a crossmatching and reservation procedure which is necessary before a unit of blood can be transfused. In addition, none of these researchers was interested in any aspect

of the inventory control problem except the desired inventory level.

The recent work of Jennings and that of Pegels and Jelmert include representations of the crossmatching and reservation requirement. Pegels and Jelmert formulated their model as a Markov chain and this implies other assumptions about the age of the blood coming in to the blood bank, the probability of transfusion at various ages, and the transition probabilities from state to state that either do not reflect the real situation or require input knowledge that is unavailable. Jennings used a simulation approach to represent his model. Therefore, no simplifying assumptions were needed to evaluate the effect of changing the desired inventory level on the wastage and shortages that occur at each level. Other simplifications in the simulation formulation make it impossible to investigate other controllable variables in the inventory system. Most of his other investigations were concerned with the effects of changing various input conditions.

CHAPTER IV

AN INVENTORY SIMULATION MODEL OF A HOSPITAL BLOOD BANK

As described in the previous section, a hospital blood bank must perform certain basic functions to carry out its purpose of stocking blood and supplying it to patients when needed. These functions include:

1. Receiving donations of blood.
2. Ordering blood from central sources.
3. Receiving and entering blood from central sources into inventory, both on a regular and emergency basis.
4. Receiving requests for crossmatching and reservation of blood for patients from doctors.
5. Crossmatching and reserving blood that has been requested.
6. Receiving requisitions for blood on reserve and issuing blood that was requisitioned.
7. Receiving returns of blood requisitioned but not transfused.
8. Removing blood from reserved inventory and returning it to regular inventory when its reservation expires, if not requisitioned.

9. Removing from inventory any units of blood that have exceeded the maximum usable age and have not been used.

In addition to carrying out the previously listed functions, the simulator must also perform a large variety of "book-keeping" tasks to measure the effectiveness of its operations.

Some of these measures are:

1. Number of requests processed.
2. Number and percent of units wasted.
3. Number of special orders processed.
4. Age of blood on transfusion.
5. Number of crossmatches performed.

The above measures are obtained for each of the eight blood groups.

This chapter presents a detailed description of how the simulation model performs each of the inventory functions; a comparison of the method used by the simulator with an actual blood bank operation; and how the collected data are used in the simulator.

In order to follow the overall sequence of operations performed by the blood bank simulator, the following simplified flow chart can be used as a guide to the generation of the various events which effect the blood bank's inventory. A detailed flow chart which shows the specific operation of each function in this simplified chart is given in Appendix V.

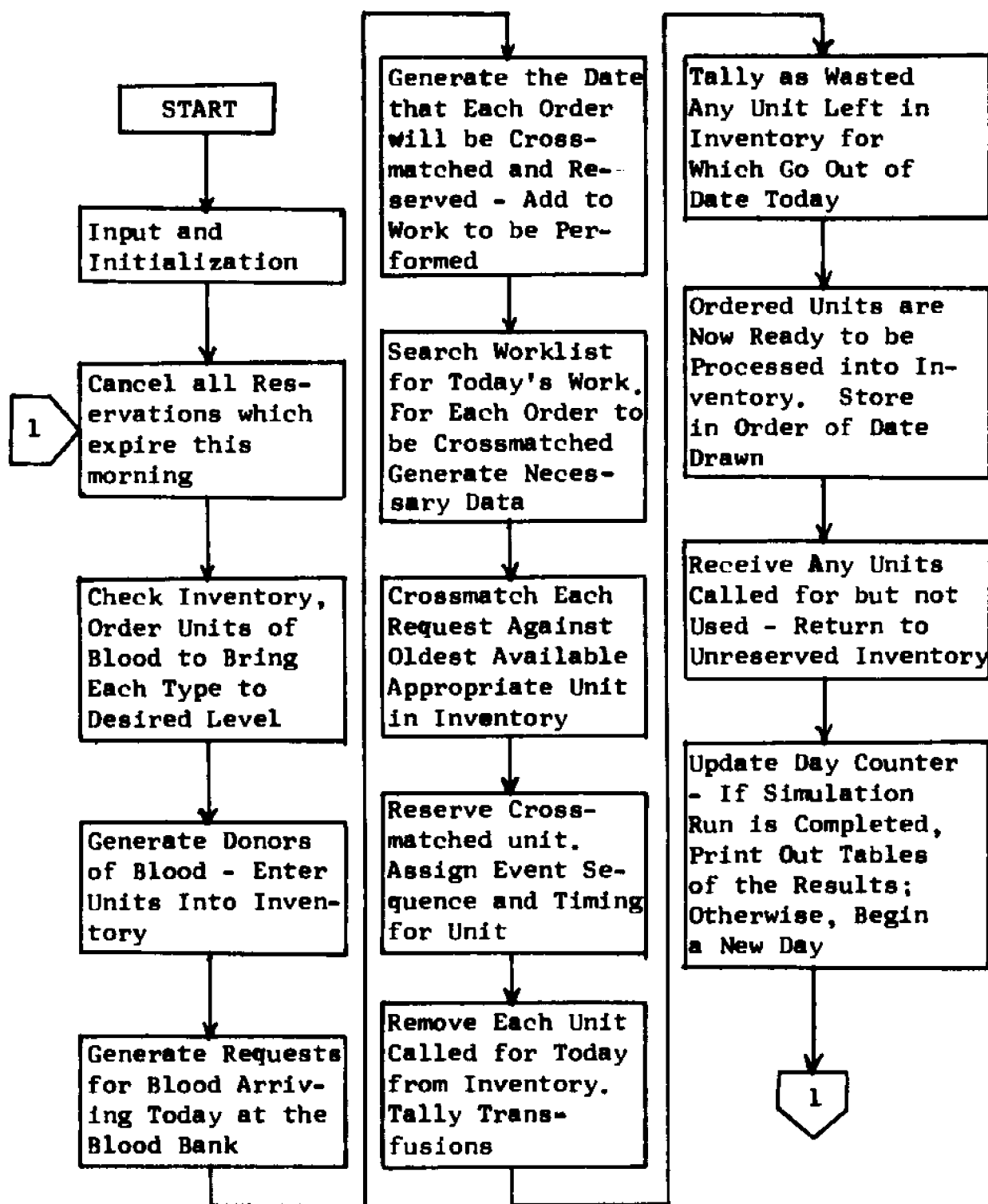


Fig. 2.--Simplified flow chart of the blood bank inventory simulation program.

Orders for Blood and Receipt
of the Ordered Blood

After expired reservations have been cancelled and "out-of-date" units have been removed from inventory, the number of units of blood of each type remaining is compared with the desired inventory level for that blood type. If the inventory is less than the desired level, orders are placed to bring it to the desired level. The desired levels for each blood type are input parameters. They can be varied from run to run to measure the effect of operating the blood bank under different desired inventory levels. To conform with the practice at Mount Sinai Hospital, these regular orders are placed only on weekdays (Monday through Friday). On Fridays, the desired levels are raised slightly to provide extra inventory for the weekend.

The units do not actually arrive until late afternoon. They are then placed in a separate storage facility until readied for entering into the regular inventory. The computer simulator generates the units when they are ordered, keeping them aside and not entering them into regular inventory until the end of the day unless a shortage occurs. For each unit ordered for inventory, the day it was drawn must be generated since the units ordered from outside sources arrive at various age levels. The age of each unit of blood, when received at the blood bank, is obtained using the observed data in the form of experience curves.¹ Experience

¹A discussion of the use of experience curves and statistical models for the generation of data is given in Appendix X.

curves exactly represent the observed data, whereas none of the statistical models that were tried provided an adequate description of the distribution of age of blood on receipt. The following table gives the cumulative relative frequency distributions (experience curves) for the age of blood received at Mount Sinai Hospital during the data collection period:

TABLE 3
AGE OF BLOOD RECEIVED - EXCLUDING DONATED BLOOD

Age in Days	Cumulative Relative Frequency Distributions							
	Blood Types							
	A+	A-	B+	B-	AB+	AB-	O+	O-
0	.0297	.0054	.0065	.0223	.0185	.2292	.0194	.0265
1	.1420	.1177	.0874	.2001	.1241	.3333	.0828	.2478
2	.2500	.3263	.1531	.3779	.3787	.5833	.1763	.5132
3	.3202	.4493	.2297	.4224	.4906	.6250	.2562	.7610
4	.3655	.6418	.3150	.6002	.6148	.7500	.3066	.8406
5	.4125	.7167	.4595	.7557	.7142	.8334	.3497	.9114
6	.4776	.7916	.5558	.8668	.8012	.9584	.4750	.9114
7	.5939	.8558	.6215	.8890	.8509	.9584	.5873	.9291
8	.6772	.9039	.7397	.9112	.8882	.9792	.7119	.9379
9	.7465	.9467	.7988	.9112	.9192	1.0000	.7616	.9467
10	.7869	.9627	.8863	.9557	.9502		.7933	.9467
11	.8364	.9787	.9169	.9557	.9689		.8574	.9467
12	.8950	.9787	.9475	.9557	.9751		.8956	.9467
13	.9445	.9894	.9694	.9557	.9751		.9481	.9732
14	.9734	.9947	.9826	.9557	.9751		.9719	.9909
15	.9859	.9947	.9848	.9557	.9876		.9870	1.0000
16	.9982	1.0000	.9849	1.0000	.9938		.9992	
17	1.0000		.9870		1.0000		1.0000	
18			.9914					
19			1.0000					

The major obstacle to describing the observed data with a statistical model was the multi-modal nature of the observed frequency distributions. The observed cumulative relative frequency distributions can serve the same purpose of a statistical model, that is, to generate representative ages for the ordered blood. The only real shortcoming in using the observed data is the large amount of memory it takes to store a complete cumulative distribution when only one or two parameters would be necessary for a statistical model. An example of the distribution of age of blood on receipt is shown below for O positive blood.

Relative Frequency Distribution

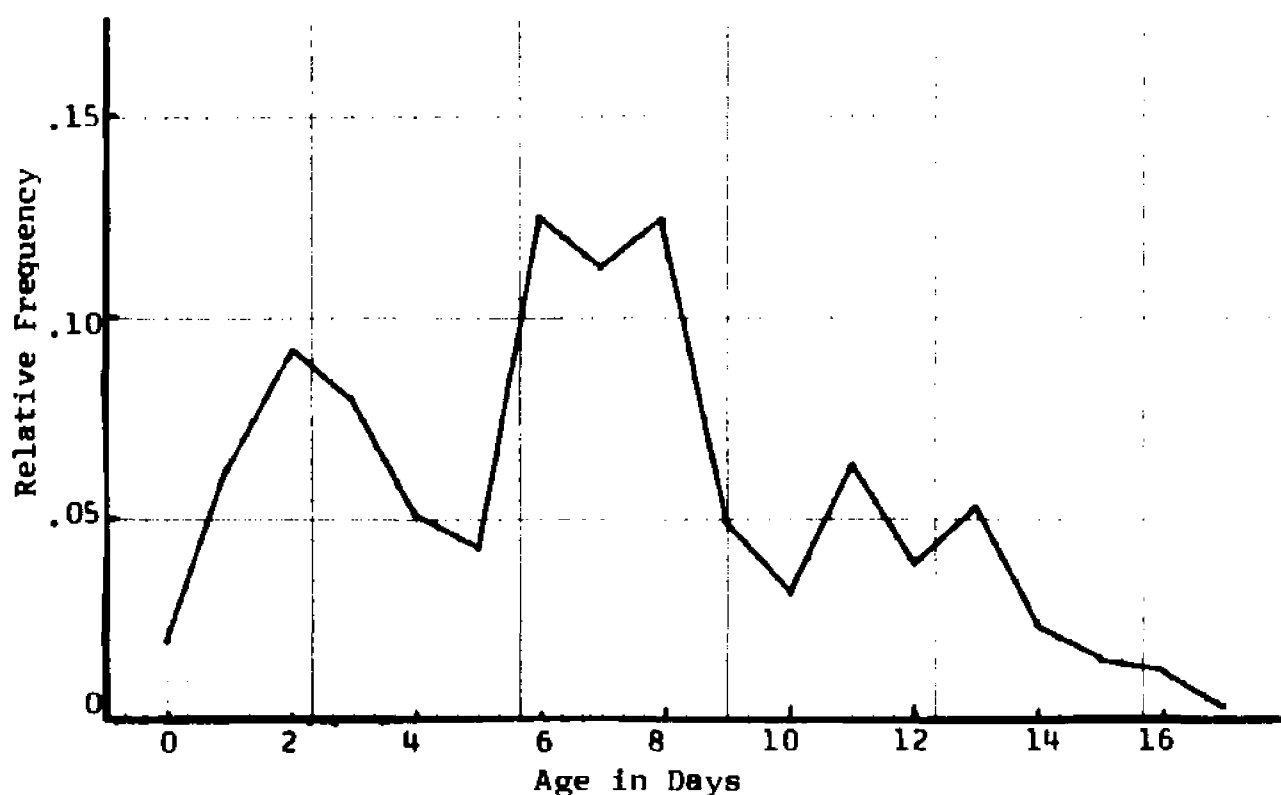


Fig. 3.--Age of ordered O positive blood on receipt.
Source: Table 3.

The Number of Units of Donated
Blood Received Per Day

While most of the blood received at the Mount Sinai Hospital blood bank is obtained from central agencies and commercial sources, some is obtained directly from donors at the hospital. Analysis of the data collected indicated that the number of units of blood of each type donated per day followed a Poisson probability distribution. The number of units of each type is generated in the simulator every day by making a random selection from a Poisson distribution whose parameter is equal to the observed mean. The average number of units donated per day by blood type is shown in the following table for the data collection period:

TABLE 4

AVERAGE NUMBER OF UNITS DONATED PER DAY	
Blood Type	Average
A+	2.154
A-	0.358
B+	0.701
B-	0.112
AB+	0.355
AB-	0.019
O+	2.467
O-	0.346

An observed distribution of the number of units donated per day and the theoretical Poisson probabilities are shown in the following

figure using O negative blood as an example:²

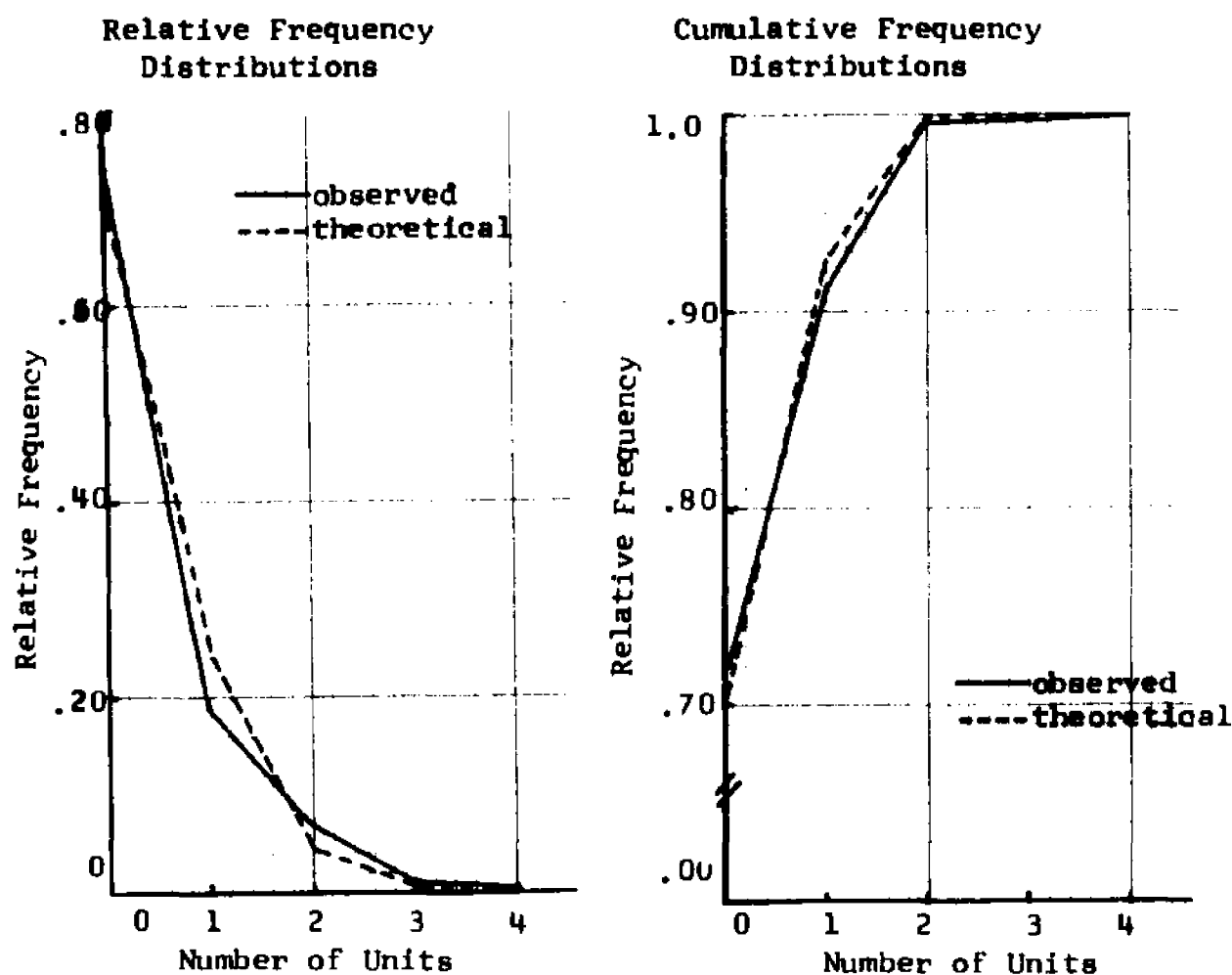


Fig. 4.--Number of units donated per day:
O negative blood. Theoretical geometric and
observed distributions.

Source: Appendix III.

The Kolmogorov-Smirnov goodness of fit test³ was performed
to verify that the Poisson distribution was a reasonable model for

²The actual and theoretical distributions of number of units
donated per day are presented for each blood type in Appendix III.

³The choice of this test and the level of significance are
discussed in detail in Appendix IX.

the generation of donated blood. There was insufficient evidence to reject this theoretical distribution. The Poisson model was therefore considered an adequate representation of the data.

Most donations of blood are made in the morning at Mount Sinai Hospital and the processing of donated blood is usually done rapidly. This blood is usually available for the patients later in the same day it was donated. In the simulator, the units of donated blood generated⁴ are entered into inventory immediately. However, since the inventory is maintained and used on an "oldest blood first" basis and the donated blood is obviously freshest, it is put at the end of the inventory list and would not be selected for a crossmatch until all older units of that type have been reserved. This might not occur even that day and most certainly would not occur until the donated units were actually available.

Requests for Crossmatching and Reservation

In most inventory simulators, the demand for the product is generated without regard to where it originated. In order to evaluate the concept of double-crossmatching, it is necessary to maintain the information on the patient associated with each request. The daily demand on the blood bank is generated in two steps: first, the number of different patients requesting each type of

⁴Generation of random events using a Poisson model is discussed in Appendix X.

blood is generated and, then, for each of these patients the number of units requested for him that day is generated. Thus, patients per day times units per patient per day yields units per day.

Generation of patients per day

Analysis of the data collected at Mount Sinai Hospital indicated that the number of patients per day for each blood type followed a Poisson probability distribution, if the weekday demand was separated from the weekend demand.⁵ Each demand was Poisson in nature but with different parameters. The Poisson probability function is represented by:

$$f(x) = e^{-u} u^x / x!$$

where $f(x)$ = the probability of having x patients on a given day,

u = the mean number of patients per day.

The following table lists the average number of patients per day for both weekdays and weekends for each blood type.

⁵The demand of each type each day would be generated independently of the demand of each other type. It was, therefore, necessary to determine if the actual demand per day of each blood type was independent of the demand for the other blood types. If the demand per day for each blood type was Poisson distributed with parameter U_i , and if these demands were independent of each other, then the demands per day, summed over all blood types would also be Poisson distributed with parameter $U = \sum U_i$. Accordingly, a statistical analysis of the total number of patients per day was performed, separately for weekdays and weekends. The observed means were 45.9 and 26.5 patients per day for weekdays and weekends respectively which were equal to the sum of the means of the individual blood types, since the mean of a sum always equals the sum of the means. The observed variances were 53.2 and 28.7 respectively. The hypothesis of independence of blood type demands was tested by comparing the observed distribution with the theoretical Poisson with parameter $U = \sum U_i$ which would have occurred

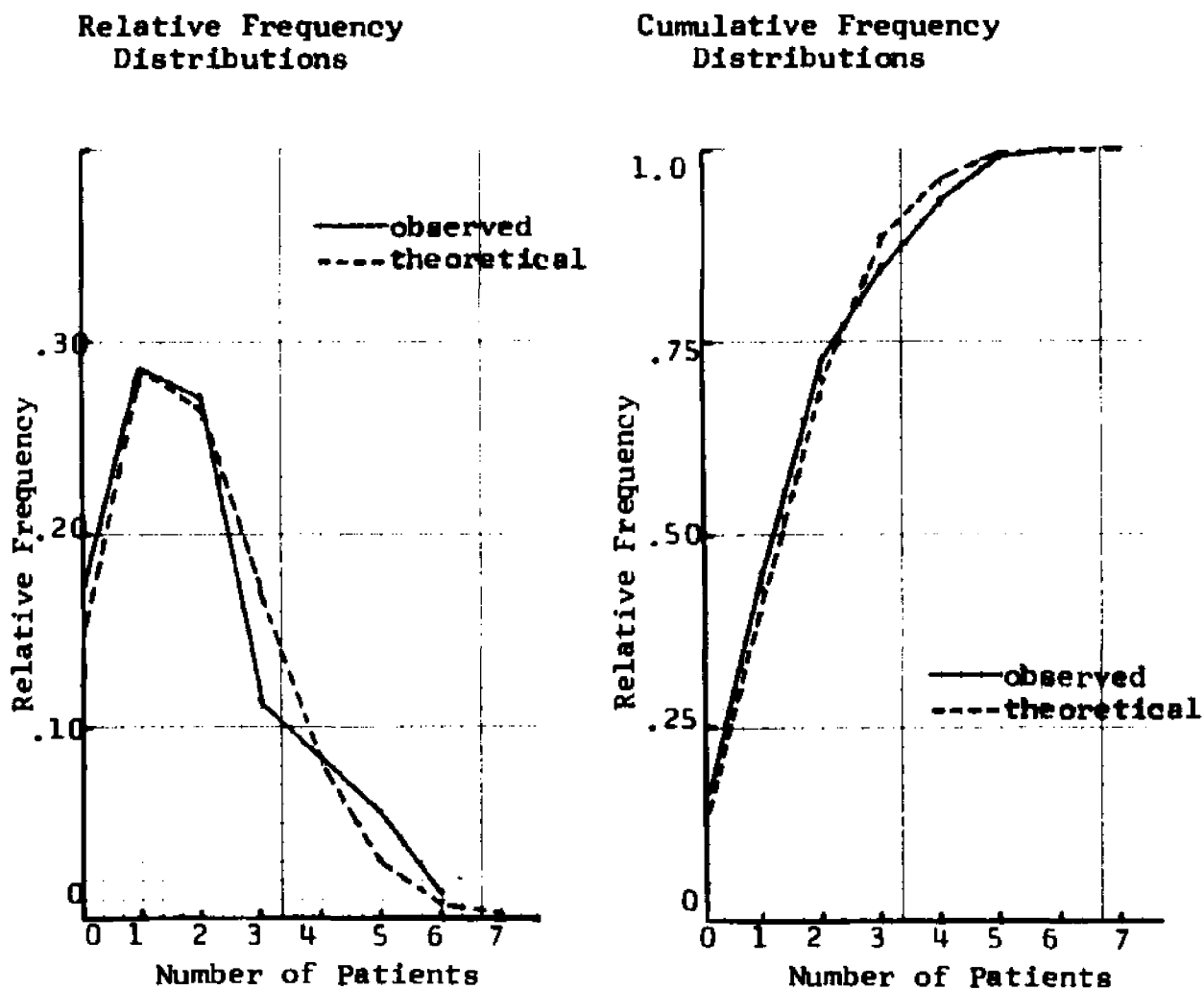
TABLE 5
AVERAGE NUMBER OF PATIENTS PER DAY

Blood Type	Weekdays (Sun-Thurs)	Weekends (Fri-Sat)
A+	15.58	9.29
A-	2.14	1.39
B+	6.35	3.79
B-	0.63	0.46
AB+	2.36	1.39
AB-	0.40	0.11
O+	16.86	8.93
O-	1.89	1.29

An example of the comparison of observed data to the theoretical Poisson distribution is shown below for patients with O negative blood on weekdays.⁶

under the independence assumption. The Kolmogorov-Smirnov procedure was used to test the "goodness of fit" between the observed data and the hypothesized model. The observed maximum differences were less than the critical values at $\alpha = .05$ level of significance, and so that there was insufficient evidence to reject the assumption of independence of demand among blood types. Therefore, each blood type's demand is generated independently of the other blood types in the simulation model. Generation of random events using a Poisson model is discussed in Appendix X.

⁶Actual and theoretical distributions of number of patients per day for weekdays and weekends are shown for each blood type in Appendix III.



Source: Appendix III.

Fig. 5.--Number of patients per day (Sunday-Thursday): 0 negative blood. Theoretical Poisson and observed distributions.

The Kolmogorov-Smirnov test of goodness of fit⁷ was performed for each of the sixteen sets of observed data against the theoretical Poisson and there was insufficient evidence to reject this model for any of the distributions.

⁷The choice of this test and the level of significance are discussed in detail in Appendix IX.

Generation of requests per patient

The observed distributions of number of requests per patient per day appeared very unusual, with each of the distributions exhibiting a very high modal class at two units per patient. An example of an observed relative frequency distribution is given below for A positive blood:

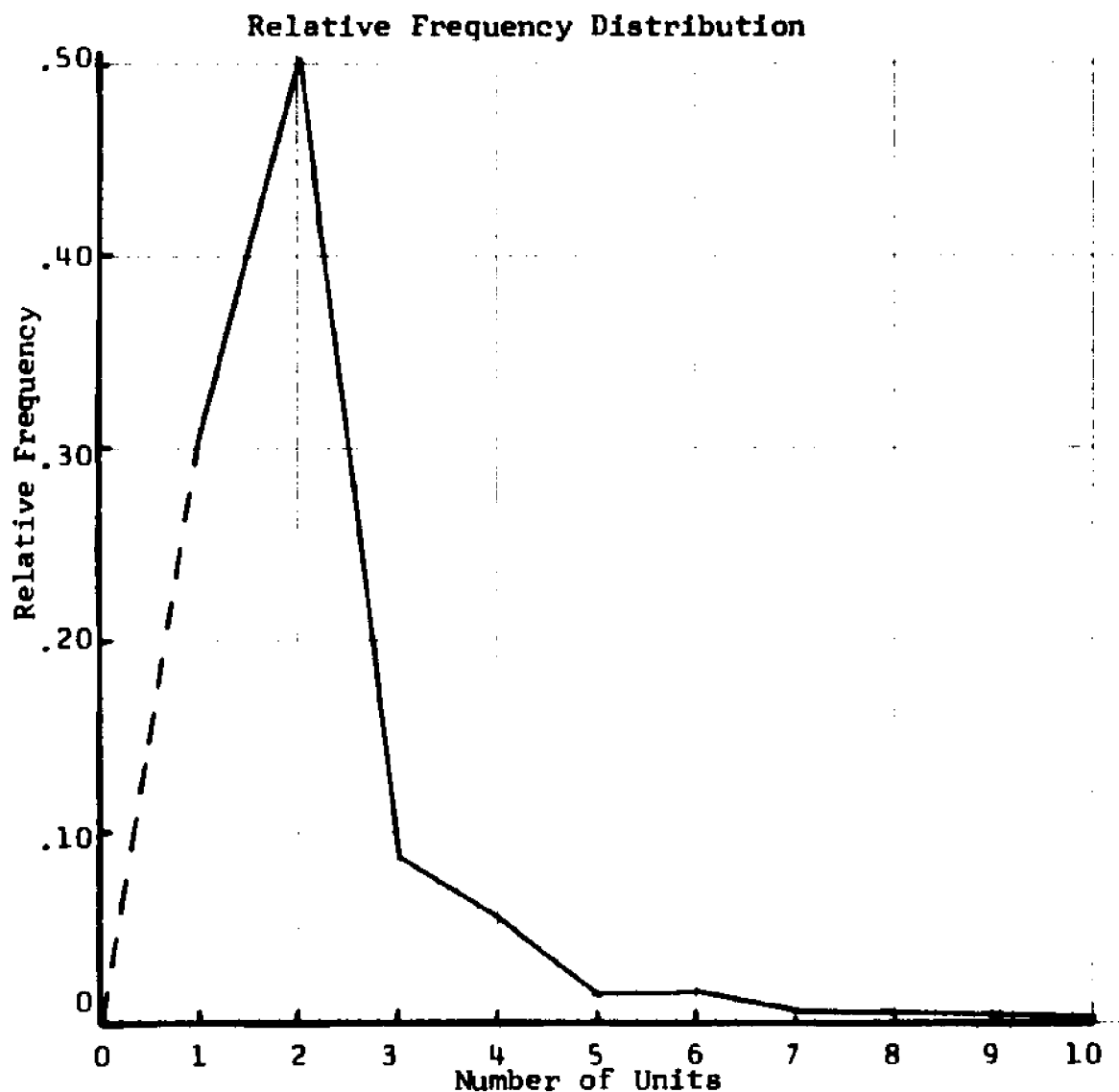


Fig. 6.--Number of units reserved per patient per day: A positive blood.

Source: Appendix III.

No simple probability model for these observed data could describe the unusual peak at two units per patient. In order to describe the observed data the following hypotheses were formulated:

1. In some cases, when a physician orders blood for a patient he is reasonably sure that the patient will need some units of blood. In these cases, it is felt that the number of units requested would follow a geometric probability distribution.
2. In cases when the physician is not sure if the patient will actually require blood, it is hypothesized that he will reserve two units to be on the "safe side".

The above hypotheses can be expressed in the following statistical model:

$$f(x) = k g(x) + (1-k) h(x)$$

where $f(x)$ = the probability of requesting x units of blood;

k = the probability of ordering exactly two units;

$1-k$ = the probability that the number of units ordered will have a geometric distribution;

$g(x) = 1$, for $x = 2$; $g(x) = 0$, otherwise;

$h(x) = p(1-p)^{x-1}$ for $x \geq 1$.

This statistical model has two parameters, k and p , which must be estimated from the observed data in order to obtain a theoretical distribution. The method of maximum likelihood⁸ was used to obtain appropriate estimators of the unknown parameters and theoretical distributions were obtained using these values.

⁸A discussion of the maximum likelihood method and its application in this instance is given in Appendix VIII.

An example of the above approach is given below for A negative blood.⁹ The estimates of k and p were .3921 and .4917 respectively. The theoretical probabilities and the observed data are given in the following table:

TABLE 6
NUMBER OF UNITS PER PATIENT FOR A NEGATIVE PATIENTS
COMPARISON OF THEORETICAL MODEL WITH OBSERVED DATA

No. of units x	$h(x) = p(1-p)^{x-1}$	$(1-k)h(x)$	Theore- tical $f(x) = kg(x) (1-k)h(x)$	Observed Relative Frequency Distribu- tion	Cumula- tive Theore- tical	Cumu- lative Observed
1	.4917	.2989	.2989	.308	.2989	.308
2	.2499	.1519	.5440	.544	.8429	.851
3	.1270	.0772	.0772	.062	.9201	.913
4	.0646	.0393	.0393	.056	.9594	.969
5	.0328	.0199	.0199	.005	.9793	.974
6	.0167	.0102	.0102	.015	.9895	.990
7	.0085	.0052	.0052	.000	.9947	.990
8	.0043	.0026	.0026	.005	.9973	.995
9	.0022	.0013	.0013	.000	.9986	.995
10	.0011	.0007	.0007	.000	.9993	.995
10+	<u>.0013</u>	<u>.0007</u>	<u>.0007</u>	<u>.005</u>	1.0000	1.000
	1.0000	.6079	1.0000	1.000		

The Kolmogorov-Smirnov test of goodness of fit¹⁰ was used to determine if the model was an adequate representation of the observed data and since there was insufficient evidence that it was not, the theoretical model was used in the simulator to generate the number

⁹Actual and theoretical distributions of number of units per patient are presented for each blood type in Appendix III.

¹⁰The choice of this test and the level of significance are discussed in detail in Appendix IX.

of units requested for each patient each day.¹¹

The simulation model thus generates a computer representation of the request slips that are received at the blood bank each day. The following table gives the values of the parameters which were used in the theoretical model to generate the number of units requested per patient per day by blood type.

TABLE 7
PARAMETERS FOR THE THEORETICAL MODEL OF NUMBER
OF UNITS REQUESTED PER PATIENT

Blood Type	Parameter of Geometric (p)	Prob. of Requesting exactly 2 units (k)
A+	.4687	.3422
A-	.4917	.3921
B+	.4731	.2847
B-	.6762	.1870
AB+	.4875	.2575
AB-	.6565	.2705
O+	.4236	.3477
O-	.4018	.3299

The Date when the Cross-match is Performed

To allow time for the crossmatching to be performed, most requests for blood other than for emergencies, are sent to the

¹¹Generation of random events using the composite model is accomplished by first making a Bernoulli trial, with probability of success = k, to determine if g(x) or h(x) is to be used for this event. If g(x) is used, x is set equal to two; if h(x) is used, x is generated using a geometric model with parameter = p. Use of the Bernoulli and geometric distributions to generate random events is discussed in Appendix X.

blood bank at least one day in advance of the day that the blood is actually needed. This accounts for the fact that most requests for crossmatching occur from Sunday to Thursday, whereas most uses of blood occur between Monday and Friday. Requests for crossmatching are not necessarily fulfilled on the day received. Some of these requests may not be crossmatched until the next day (or later) either because: (a) an exceptionally heavy workload and blood not immediately needed; or (b) because the date indicated by the physician was several days in the future and it would be very wasteful to keep a unit on reserve long before it was needed.

A statistical analysis of the number of elapsed days between the date the request for crossmatch was received and the date the actual crossmatching was performed. The analysis indicated that the distribution of these times could be described by a geometric type of probability distribution. This distribution corroborates the fact that most crossmatches are performed on the same day as requested (0 days elapsed), less are performed on the following day (1 day elapsed), and less and less are performed on each succeeding day. The theoretical model used to represent the days between the date of request for crossmatch and the date of crossmatch is given by:

$$f(x) = p(1-p)^x, \text{ for } x \geq 0$$

where $f(x)$ = the probability of x days between request and crossmatch;

p = the parameter of the geometric distribution and represents the percent of crossmatches that are performed on the day requested.

The observed data were used to obtain estimators of the parameters of the geometric distribution for each blood type. Maximum likelihood estimators were used which resulted in the

following estimates:¹²

$$\bar{p} = 1/(\bar{x} + 1)$$

where $\bar{p}$ = the maximum likelihood estimator;

$\bar{x}$ = the mean of the observed data.

The following table lists the observed mean elapsed time and the estimated parameter for each blood type:

TABLE 8
TIME BETWEEN REQUEST FOR CROSSMATCH
AND PERFORMANCE OF CROSSMATCH

Blood Type	Average No. of elapsed days	Estimated Parameter (Percent of Cross- matches Performed on same day)
A+	0.136	88.0%
A-	0.102	90.7
B+	0.127	88.7
B-	0.149	87.1
AB+	0.186	84.3
AB-	0.243	80.4
O+	0.124	89.0
O-	0.170	85.4

The theoretical distributions were also tested for goodness of fit against the observed data.¹³ There was insufficient evidence to reject the geometric probability distribution as an appropriate model for generating the number of days between the date requested

¹²The standard geometric distribution is $p(1-p)^{x-1}$. The maximum likelihood estimator of its parameter is simply $1/\bar{x}$. The modification required in this case results from shifting from $x-1$ to x in the exponent.

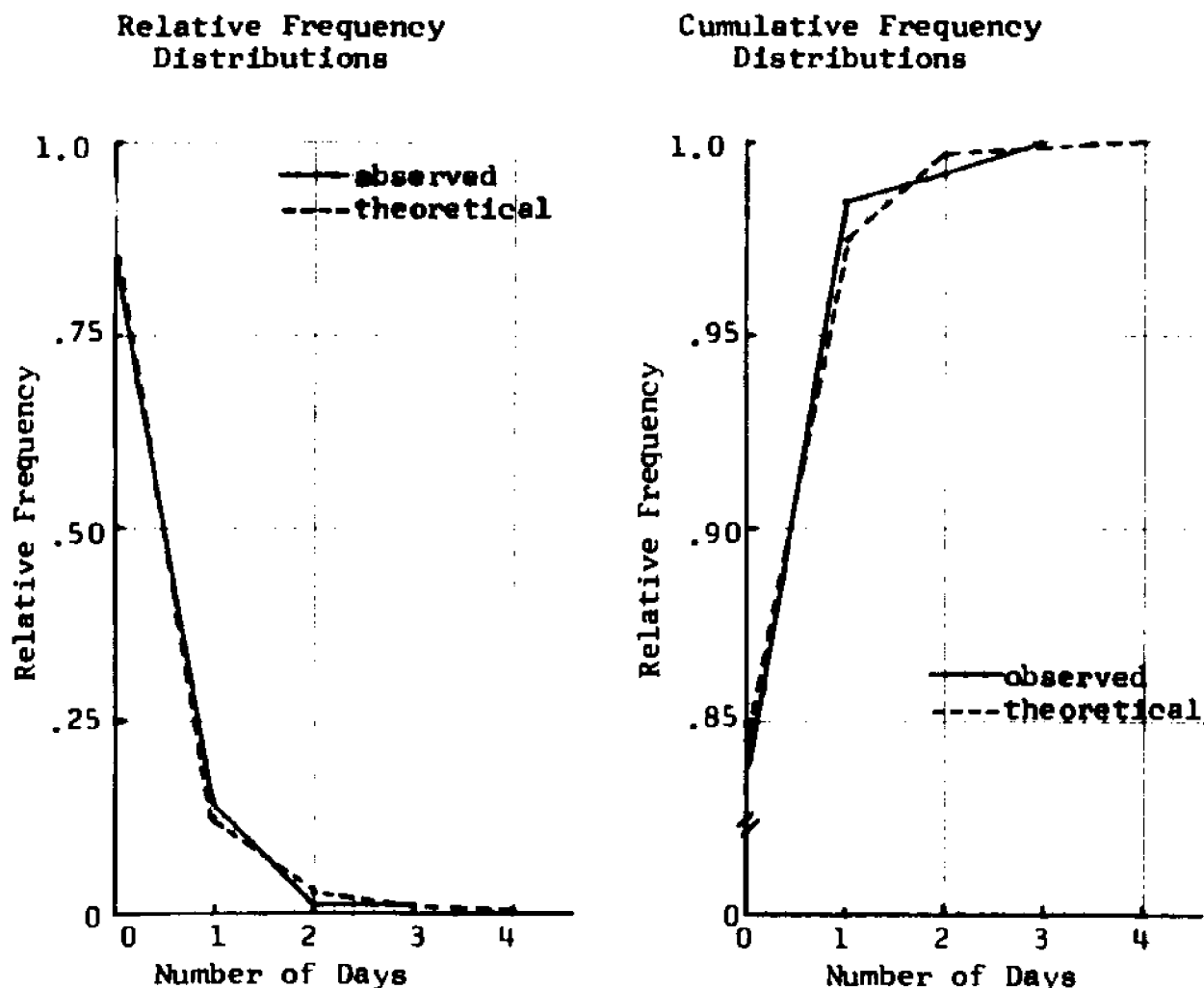
¹³The Kolmogorov-Smirnov test was used. A discussion of this test and its application is given in Appendix IX.

and the date actually crossmatched.¹⁴ These elapsed days are generated right after the requests are created and the elapsed time is added to the date of the request to arrive at the date the crossmatching will take place in the simulated model. This date is stored together with the other information pertaining to the request. Since a doctor may have requested several units for one patient, these requests are processed together and the same crossmatching date is assigned to all of the requests for a given patient.

An observed distribution of days elapsed between the date a crossmatching was requested and the date it was actually performed and the theoretical geometric probabilities are shown in the following figure using AB positive blood as an example:¹⁵

¹⁴Generation of random events using a geometric model is discussed in Appendix X.

¹⁵The actual and theoretical distributions of days elapsed between date requested and date crossmatched are presented for each blood type in Appendix III.



Source: Appendix III.

Fig. 7.--Time from request to crossmatch:
AB positive blood. Theoretical geometric and
observed distributions.

The Events Following a Reservation and Their Timing

When a date has been established in the simulator for the crossmatching and reservation to take place, all the information about the order (patient identification, number of units requested, date requested and date to be crossmatched) is added to a list containing the crossmatching and reservation work that the blood bank

has to perform at the appropriate time. Before processing any of this day's requests, this list contains any work that arrived on previous days and is scheduled to be performed today and on succeeding days. After assigning crossmatching dates to this day's requests and adding the order information to the list, it contains all the crossmatching work to be performed today plus some of the work that will be done on future days.

After the list is completed, the simulator checks it and finds each of the orders for which crossmatching and reservation are to be performed today. If a particular order is to be cross-matched on this day, then a number of units of blood in inventory equal to the number of units requested will be reserved. The simulator must therefore determine what will happen to each of the reserved units. There are three possibilities once a unit of blood has been reserved for a patient: it will either be requisitioned by the doctor and called for, or the reservation will be cancelled when it expires. If the unit of blood is called for, it will either be transfused or it will be returned to inventory. Thus, each reservation must involve one of the following three event sequences:

1. Cancellation of Reservation.
2. Call for and Transfusion.
3. Call for and Return.

The simulator must therefore provide a mechanism for deciding which event sequence to assign to each reservation and to determine when each event in the sequence will take place. In the simulator,

the sequence assignment and its timing is performed immediately before the reservation is made for a unit of blood because the complete order information is available. The appropriate event sequence and its timing can then be assigned to each unit of blood as it is reserved in the process of "filling" the patient's order.

It is important to remember that although the information has been created as to what is going to happen to the unit of blood and when it is going to happen for the current reservation, it is not available to the simulator until the time arrives for the event to occur. Thus, the simulator, like the real blood bank, does not know whether the unit will be called for, or if it will be returned, etc., or when, unless the particular event occurs and it is therefore carried out at that time. The methods used in the simulator to generate the event sequence and its timing for each patient's requests are discussed in the following sections.

Generation of the number of units to be requisitioned

On an overall basis approximately 45 percent of all units reserved are eventually requisitioned.¹⁶ However, the statistical analysis of the data collected indicated that the percentage of units requisitioned was not constant for all order sizes (an order is the number of units requested for a patient on one day). The following table shows how the probability of a unit being called for is related to the size of the order, of which this particular

¹⁶Excluding requests for Open Heart Surgery.

reservation is a part:

TABLE 9
RELATIONSHIP OF PERCENT OF UNITS CALLED
FOR TO THE NUMBER OF UNITS REQUESTED

Number of Units Requested	Avg. Number of Units Called For	Percent Called For
1	0.37	37%
2	0.68	34
3	1.49	50
4	2.34	59
5	2.86	57
6	4.16	69
<u>7 and over</u>	<u>6.68</u>	<u>83</u>
Overall	0.92	45%

An examination of the above table shows that reserved units that are part of large orders are more likely to be called for than reserved units that are part of small orders. Since the order size is generated by the simulator, this information is available and can be used to generate call for behavior which is a realistic estimate of that encountered by a hospital blood bank. Accordingly, a statistical analysis of call for data was performed to obtain the conditional distributions of the number of units requisitioned, for different numbers of units requested. These conditional probabilities are shown in TABLE 10. A statistical model was not found which could reasonably describe the conditional distributions so that the observed data were used directly by the simulation model to generate the number of units to be requisitioned out of each order.¹⁷

¹⁷A discussion of the use of observed data, in the form

TABLE 10
 CONDITIONAL DISTRIBUTIONS OF NUMBER OF
 UNITS REQUISITIONED FOR DIFFERENT
 NUMBERS OF UNITS RESERVED
 (ORDER SIZE)

Number Called For	Number of Units Reserved (Order Size)									
	1	2	3	4	5	6	7	8	9	10
0	63.1%	60.7%	33.2%	16.2%	14.9%	6.2%	0.0%	5.0%	0.0%	0.0%
1	36.9	10.6	10.7	6.4	5.4	1.6	0.0	0.0	0.0	0.0
2		28.7	30.3	32.1	20.3	12.5	9.1	0.0	0.0	0.0
3			25.8	17.5	21.6	15.6	9.1	0.0	16.7	0.0
4				27.8	13.5	15.6	9.1	10.0	0.0	0.0
5					24.3	10.9	0.0	10.0	0.0	25.0
6						37.5	9.1	10.0	0.0	0.0
7							63.6	25.0	0.0	0.0
8								40.0	33.3	0.0
9									50.0	25.0
10										50.0
Mean (Units)	0.37	0.68	1.49	2.34	2.86	4.16	5.82	6.45	7.67	8.75

Date and assignment of units
to be requisitioned

If at least one unit out of an order is to be called for, it is necessary to generate the date when the blood bank will be requested to supply the unit(s). Furthermore, the simulator has to select which units of those that will be reserved are to be supplied in response to the requisition. To conform to the actual practice at the blood bank, the simulator selects the oldest units among those reserved as the ones to be called for when the requisition actually arrives, although this assignment cannot be made until the reservations are carried out. At this time the simulator does

of cumulative relative frequency distributions, to generate random events is given in Appendix X.

determine the date when the blood will be requisitioned from the blood bank.

A statistical analysis of the data indicated that the number of elapsed days between the date of a reservation and the date called for could not be described by a simple statistical distribution. While most units of blood were called for on the same day they were crossmatched, a large percentage were also called for on the next day, after which the relative frequencies declined rapidly. A composite model of the following form was hypothesized to describe the observed data:

$$f(x) = k g(x) + (1-k) h(x)$$

where $f(x)$ = the probability of x days elapsing between date crossmatched and date called for;

k = the probability of the unit being called for on the same day as it was crossmatched ($x=0$);

$1-k$ = the probability of the unit not being called for on the same day as it was crossmatched;

$g(x) = 1$, for $x = 0$; $g(x) = 0$, otherwise;

$h(x) = p(1-p)^{x-1}$, for $x \geq 1$;

p = the parameter of the geometric distribution of the number of days elapsed for those not called for on the same day.

The following table gives the average elapsed time between the date reserved and the date called for, by blood type, and the maximum likelihood estimators¹⁸ of the parameters of the theoretical composite distributions that were used to generate the elapsed time in the simulator.¹⁹

¹⁸A discussion of the maximum likelihood method and its application in this instance is given in Appendix VIII.

¹⁹Generation of random events using the composite model

TABLE 11
ELAPSED TIME FROM DATE OF RESERVATION
TO DATE CALLED FOR BY BLOOD TYPE

Blood Type	Average Elapsed Time (days)	k (Percent Called for on Same Day)	Parameter of Geometric (Percent Called For on Next Day) ^a
A+	0.4685	.594	.8681
A-	0.4233	.632	.8703
B+	0.4884	.588	.8389
B-	0.3953	.605	1.0000
AB+	0.4302	.626	.8661
AB-	0.1818	.818	1.0000
O+	0.5038	.573	.8475
O-	0.3594	.703	.8278

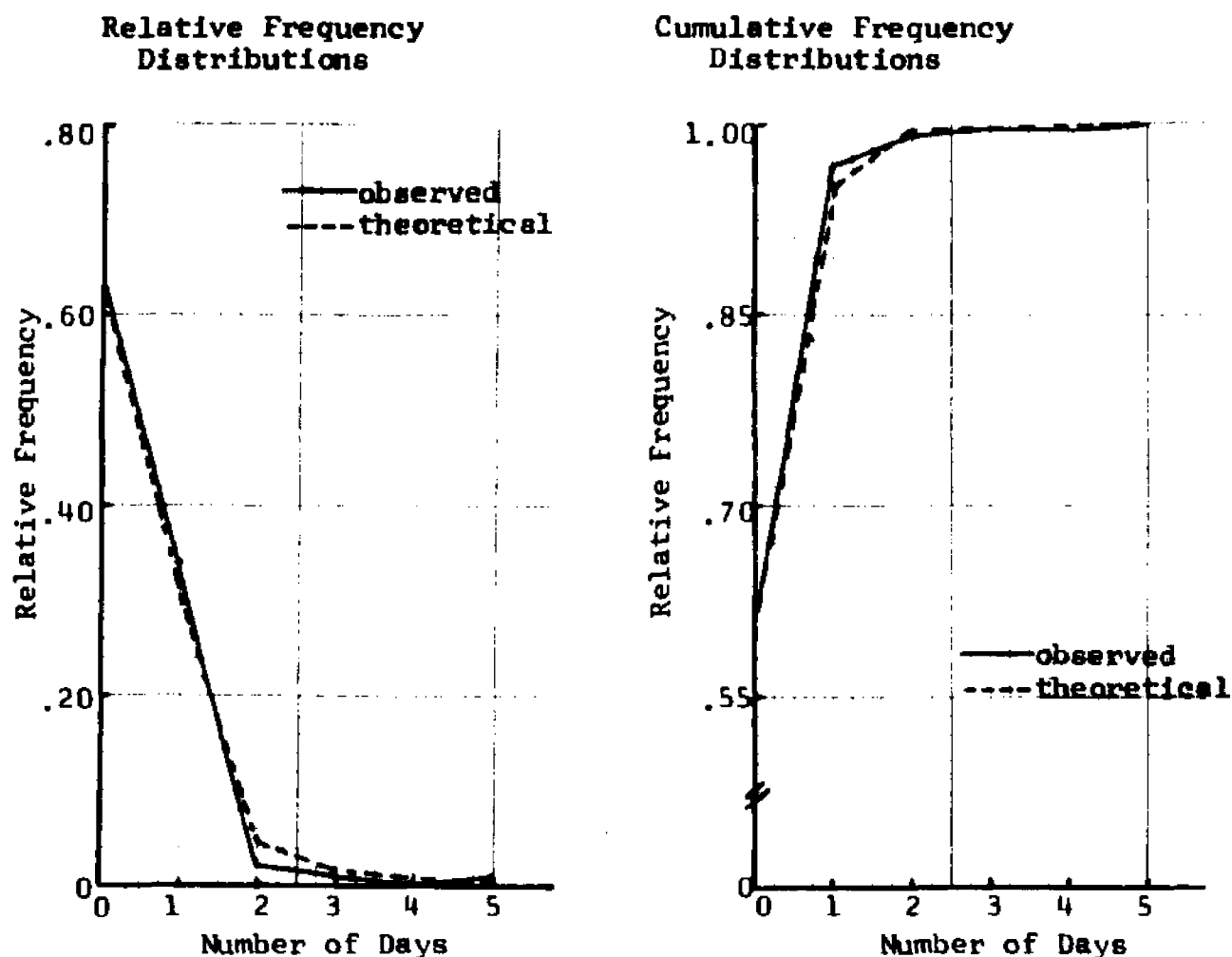
^a Given not called for on same day.

The theoretical composite distributions were tested for goodness of fit.²⁰ The results indicated that there was no evidence that this statistical model was not a reasonable representation of the actual observed data. An example of the observed data and the theoretical model used to describe it in the simulator is given in Figure 8.²¹

is accomplished by first making a Bernoulli trial, with probability of success = k , to determine if $g(x)$ or $h(x)$ is to be used for this event. If $g(x)$ is used, x is set equal to zero; if $h(x)$ is used, x is generated using a geometric model with parameter = p . Use of the Bernoulli and geometric distributions to generate random events is discussed in Appendix X.

²⁰ The choice of the test of goodness of fit and its application is discussed in Appendix IX.

²¹ Actual and theoretical distributions of the elapsed time between date reserved and date called for are presented for each blood type in Appendix III.



Source: Appendix III.

Fig. 8.--Elapsed time between date of reservation and date called for: AB positive blood. Theoretical geometric and observed distributions.

Generation of the number of units to be returned

All the units called for by the physician may not actually be transfused. Some of the units may be returned to the blood bank, if they are not needed, even though they had been requisitioned. On an overall basis, some 27 percent of all units called

for were observed to be returned. This percent is not constant for all cases but varies with the number of units which were called for from a given order. The following table shows the average number of units returned and percent of units returned for different numbers of units called for.

TABLE 12
RETURNS RELATIVE TO NUMBER CALLED FOR

Number Called For	Average Number Returned	Percent Returns
1	0.20	20%
2	0.59	29
3	1.14	38
4	0.82	20
5	1.18	24
6	2.03	34
<u>7 and over</u>	<u>1.58</u>	<u>15</u>
Overall	0.56	27%

Because the probability of a unit being returned was related to the number of units requisitioned, a statistical analysis was performed to obtain the conditional distributions of the number of returns for different numbers of units called for. A statistical model was not found which adequately described these conditional distributions so the observed relative frequencies were used in the simulator to generate return patterns which reflect the real experiences of the blood bank.²² The observed conditional distributions of the number of units returned for different numbers of

²²A discussion of the observed data, in the form of cumulative relative frequency distributions, to generate random events is given in Appendix X.

units called for is shown in TABLE 13.

TABLE 13
NUMBER OF UNITS RETURNED RELATIVE
TO NUMBER OF UNITS CALLED FOR
(ENTRIES IN CELLS REPRESENT
PERCENTAGES)

Number of Returns	Number of Units Called For									
	1	2	3	4	5	6	7	8	9	10
0	79.7	64.4	47.6	56.8	53.6	41.4	50.0	63.6	14.3	40.0
1	20.3	12.2	16.1	19.3	10.7	10.3	16.7	9.1	14.3	0.0
2		23.4	10.7	13.6	17.9	6.9	0.0	9.1	42.9	40.0
3			25.6	5.7	7.1	10.3	25.0	9.1	0.0	0.0
4				4.5	3.6	13.8	0.0	9.1	14.3	0.0
5					7.1	10.3	8.3	0.0	14.3	20.0
6						6.9	0.0	0.0	0.0	0.0
7										
8										
9										
10										
Mean (units)	0.20	0.59	1.14	0.82	1.18	2.03	1.33	0.91	2.29	1.80

Date and Assignment of
units to be returned

If at least one return of those that were to be called for is indicated in the simulation, it is necessary to generate a date when it would return to the blood bank. In addition, it is necessary to determine which of those units that are to be called for are to be returned. The transfusions of the units of blood to the patient are made without any reference to the particular unit's status. Those units not transfused and returned are therefore assigned in a random manner among the units called for. The actual determination is not made until the crossmatch and reservation are performed. This is because the call for assignment is

made at that time and the returning unit must be selected from among the called for units. The simulator does, however, generate the date when these units will be returned at this point in the program.

A statistical analysis was performed on the elapsed time between the date a unit was called for and the date it was returned. The observed data were capable of being represented by a geometric type of probability function of the following form:

$$f(x) = p(1-p)^x, \text{ for } x \geq 0$$

where $f(x)$ = the probability of x days between reservation and call for;
 p = the parameter of the geometric distribution which is also the percent of units returned on the same day called for ($x=0$).

The following table gives the average elapsed time between the date reserved and the date called for by blood type and the maximum likelihood estimators of the parameters of the theoretical geometric distributions that were used to generate elapsed time in the simulator.²³ The theoretical geometric distributions were tested for goodness of fit.²⁴ The results indicated insufficient evidence to reject the null hypothesis. Consequently, this statistical model was considered a reasonable representation of the actual observed data. An example of the observed data and the theoretical model used to describe them in

²³ Generation of random events using a geometric model is discussed in Appendix X.

²⁴ The Kolmogorov-Smirnov test was used. The choice of this test and its application is discussed in Appendix IX.

TABLE 14
ELAPSED TIME FROM DATE CALLED FOR
TO DATE RETURNED BY BLOOD TYPE

Blood Type	Average Elapsed Time (days)	Parameter of Geo- metric Distribution (Percent Returned on Same Day)
A+	0.246	80.2%
A-	0.171	85.4
B+	0.401	71.4
B-	0.111	90.0
AB+	0.250	80.0
AB-	0.000	100.0 ^a
O+	0.244	80.4
O-	0.370	73.0

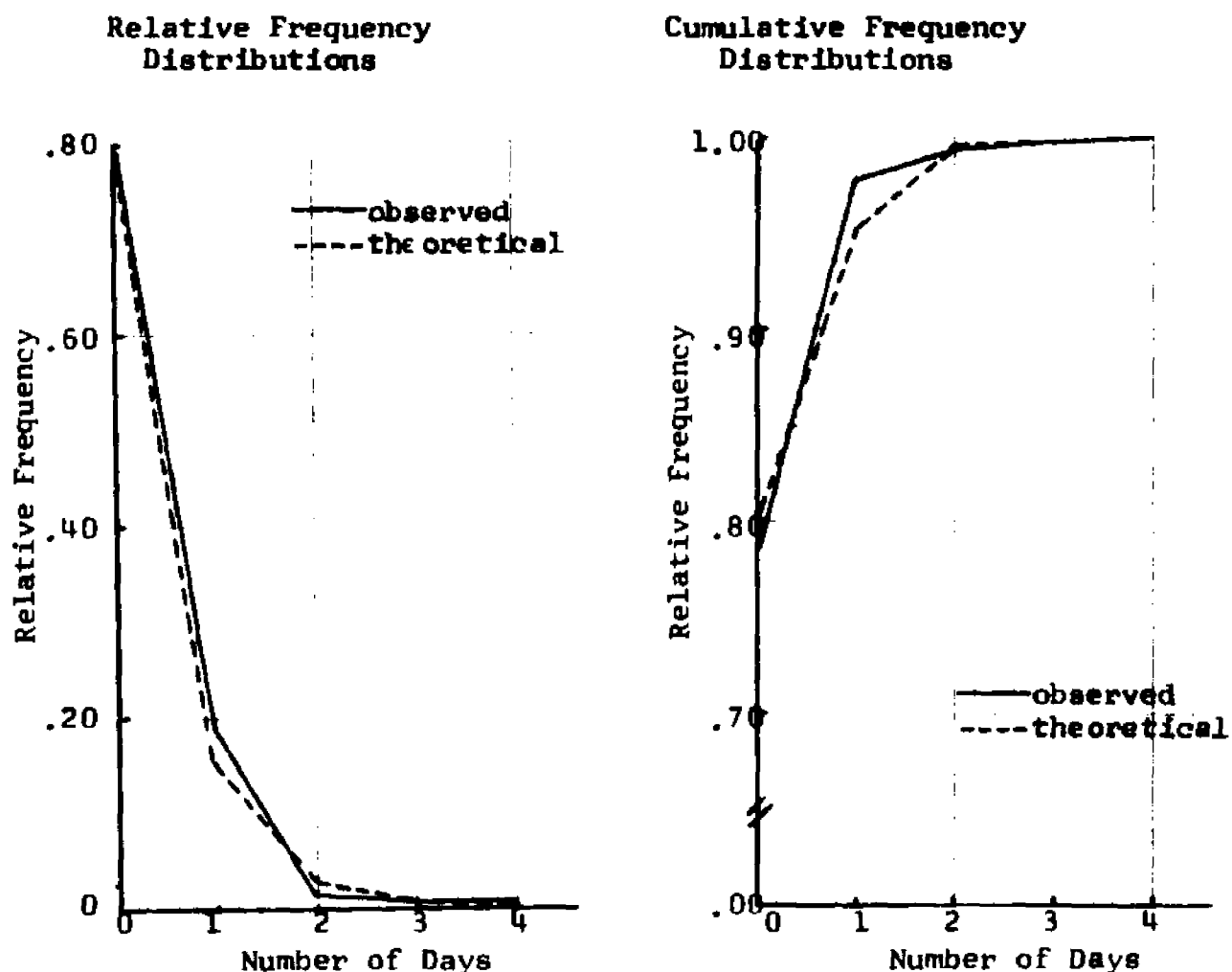
^aAll returns on same day as call for.

the simulator is given in Figure 9.²⁵

Generation of the date a reservation will be cancelled

If the physician does not call for all the units that he has requested, the reservation period will lapse for those not called for and will be cancelled. Thus, if some units in the order are not to be called for, the simulator must generate the date that these reservations will be cancelled. Mount Sinai Hospital policy requires cancellation of uncalled for reservations on the first morning after 24 hours have elapsed, unless it was an urgent or emergency request or unless the doctor requests an extension of the reservation. Most reservations are cancelled two days after they were made, with some cancellations on the very

²⁵ Actual and theoretical distributions of the time between call for and return are presented for each blood type in Appendix III.



Source: Appendix III.

Fig. 9.--Time from call for to return:
0 positive blood. Theoretical geometric and
observed distributions.

next day after reservation and an even smaller number of cancellations after three and more days.

A statistical analysis of the observed data on elapsed time between reservation and the cancellation of the reservation disclosed the expected pattern. The distribution of time from crossmatching to cancellation shows a marked modal class at 2 days

which makes it difficult to describe the observed data with any simple probability model. A composite model was hypothesized which considers the nature of the process involved in determining when a reservation will be cancelled. This model has the following form:

$$f(x) = k g(x) + (1-k) h(x)$$

where $f(x)$ = the probability of x days elapsing between crossmatching and the cancellation of the reservation;

k = the probability that a request will be cancelled on the day the hospital policy indicates;

$(1-k)$ = the probability that the reservation will not be cancelled in accordance with the standard policy;

$g(x) = 1$, for $x = 2$; $g(x) = 0$, otherwise;

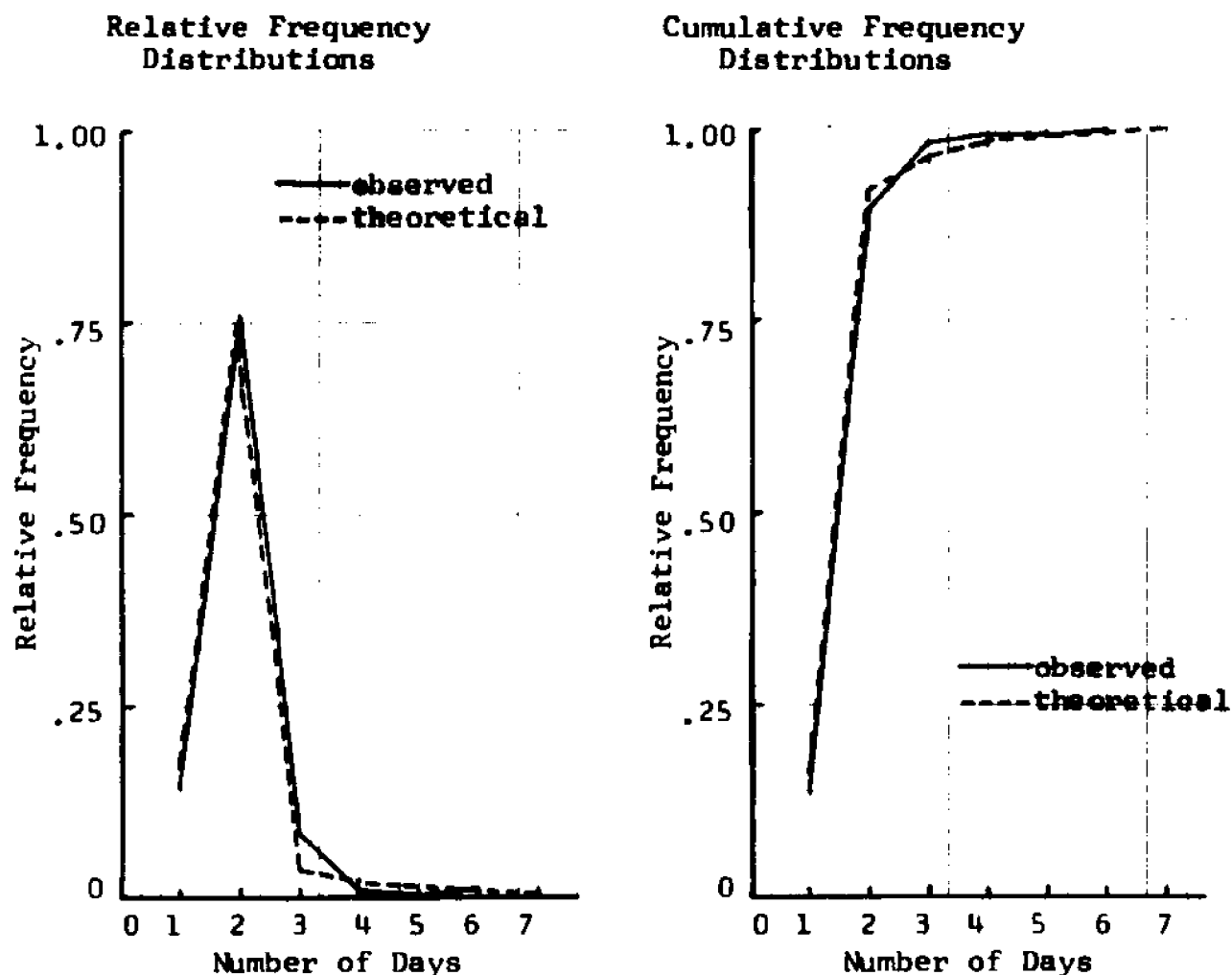
$h(x) = p(1-p)^{x-1}$, for $x \geq 1$.

This statistical model has two parameters, k and p , which must be estimated from the observed data in order to obtain a theoretical distribution. The method of maximum likelihood²⁶ was again used to obtain estimators of these parameters. Theoretical distributions were obtained using these estimates. An example of the above approach is given here for O negative blood.²⁷ The estimates of k and p were .6773 and .5001 respectively. The observed relative frequency distribution and the theoretical

²⁶A discussion of the maximum likelihood method and its application in this instance is given in Appendix III.

²⁷Actual and theoretical distributions of the time from crossmatching to reservation cancellation are presented for each blood type in Appendix III.

probability distribution are shown in the following figure.



Source: Appendix III.

Fig. 10.--Time from crossmatch to taken-off-reserve: 0 negative blood. Theoretical composite and observed distribution.

The theoretical distributions were tested for goodness of fit to verify that the model was an adequate representation of the observed data.²⁸ Since there was insufficient evidence that it

²⁸The choice of a goodness of fit test, and its application is discussed in Appendix IX.

was not adequate, the theoretical model was used in the simulator to generate the date on which units of blood are taken off reserve, if not requisitioned.²⁹ The parametric values were used in the simulator to generate the time from crossmatch and reservation of a unit of blood to cancellation of the reservation is shown in the following table:

TABLE 15
PARAMETERS FOR THEORETICAL MODEL OF ELAPSED
DAYS BETWEEN RESERVATION AND
CANCELLATION OF RESERVATION

Blood Type	Parameter of Geometric (p)	Probability of following hospital policy (k)
A+	.4538	.7833
A-	.5396	.7685
B+	.4303	.6423
B-	.4566	.8098
AB+	.4943	.7587
AB-	.8700	.8000
O+	.4596	.7179
O-	.5001	.6773

Performance of the Actual Crossmatching
and Reservation of Requested Units

At this point, the simulator has located an order to be crossmatched on this day and has generated the information necessary to process each unit requested. It is now able to reserve

²⁹Generation of random events using the composite model is accomplished by first making a Bernoulli trial, with probability of success = k, to determine if g(x) or h(x) is to be used for this event. If g(x) is used, x is set equal to two; if h(x) is used, x is generated using a geometric model with parameter = p. Use of the Bernoulli and geometric distributions to generate random events is discussed in Appendix X.

units of blood for the patient and to assign the generated event sequence and its timing to each reserved unit. The following information about the order is available in the simulation:

1. Patient identification and blood type.
2. Date requested.
3. Number of units requested.
4. Date to be crossmatched.
5. Number of units to be called for.
6. Date the units will be called for.
7. Number of units to be returned.
8. Date the units will be returned.
9. Date of cancellation of reservation.

The simulator uses the patient's blood type to determine the type of blood it should use from the blood bank. It then finds the oldest unit of this blood type not currently reserved and crossmatches it against this patient's blood. The simulator identifies available units of blood by examining its inventory record. Thirteen locations are provided by the simulator to record information for each unit of blood. The first three items of information are characteristics of the unit which do not change once it is put into inventory, the next five items are used to describe the current reservation, and the last five to accumulate data about the unit's history while in inventory.

Inventory records are maintained in order of the age of blood, within blood types, with the oldest unit first. The simulator examines the list of units in inventory of the appropriate blood type until it finds one not on reserve. This is indicated

by no entries in the items of information about the current reservation. Reservation is then made for the patient by inserting his identification number into the fourth space and the current date into the fifth space.

The determination as to whether this unit is one that will be called for is made now. The reservations for this order are made by finding the oldest units first and the oldest units are the ones that will be disbursed if the entire order is not called for. Therefore, the first N units reserved for this patient are assigned to be requisitioned, where N is the number of units to be called for. These units get the date they will be called for inserted into their seventh space, which otherwise is left blank. If M units were generated to be returned out of the N units called for, the program randomly selects M units out of the N units and indicates they are to be returned by putting the date for return into the eighth space. Those units not to be called for get the date of reservation cancellation inserted into their eighth space.

The entire sequence of events that will happen to each unit reserved for this patient's order has now been included in the inventory record of that unit of blood. This procedure is carried out by the simulator for each order in the worklist whose scheduled date for crossmatching is the current date. After all the day's crossmatching has been completed, the requests for crossmatching and reservation which have been processed are removed from the list of work to be performed by the blood bank. The information relating to all the other events that affect the

inventory status of the blood bank is now contained in the inventory file.

Processing of Requisitions for Reserved
Blood (Call for Slips)

The only units that can be called for are those which are on reserve. When all of the day's crossmatching and corresponding reservations have been completed, the program can begin processing the actual requests for blood. In the hospital blood bank, of course, crossmatching and requisitions are being continuously performed during the day, but a requisition for a particular patient cannot be processed until units have been reserved for that patient. Thus, the simulator, by performing all the crossmatches first and then processing all the requests, does not reproduce the exact sequence of these events at the blood bank. However, it does simulate the actual effect of these events on the inventory of the blood bank.

The units of blood that would have been supplied when the requisitions were received by the blood bank have already been identified by the simulator by the insertion of a date in the seventh space for those units of blood. The simulator searches through the inventory list to find all units with the current date in this position. When it finds such a unit, the status of that unit is changed, to make it unavailable. The unavailability status may be permanent if the unit is actually transfused or it may only be temporary if the unit is returned. In either case, the status change means that the unit no longer

exists as far as the simulator is concerned. If a unit is not transfused and is returned, the simulator still has available all the information about it (i.e., unit number, blood type, date drawn, and date received as well as all the statistics accumulated for it). It can then recreate the record of that unit in its appropriate position in the inventory list. If the unit was actually transfused (the return date in the eighth position is blank), a transfusion is tallied and the statistics for this unit are accumulated into the appropriate output tables. All units indicated to be called for on this day are similarly processed by the simulator.

Expiration of Life of a Unit of Blood

Since the simulator processes all the call forms arriving on the current day together, once they have been sent out, no other units will be used on this date. Any units still in inventory after all requisitions have been processed for which this was the last day of useful life (i.e., they were 21 days old today) will go "out-of-date" first thing tomorrow morning and be wasted. As a practical matter, the simulator searches through the inventory list after the call forms have been processed instead of waiting until the next morning. It finds all those units still in inventory that are 21 days old by comparing the date drawn (in the second information position of the unit) with the current date. When an expired unit is found, its status is changed to unavailable and it is tallied as wasted.

Deletions from and Additions to Inventory

At this time the inventory list contains the records of many units no longer available. The units that were transfused and those that expired are permanently removed while those that were called for but will be returned are temporarily unavailable. The simulator carries out an inventory housekeeping by posting all statistics that have been accumulated for the units permanently removed into the statistical output tables and by deleting the complete record of those units from the inventory.

The simulator then assumes that all the ordered blood has been fully processed and is not available to be added to the regular inventory listing. (If the blood bank needed extra units for cross-matching, the processing of the ordered blood would have been accelerated and those units would have already been added to inventory.) These units are added to the old inventory, using the date drawn as the criterion for determining their position in the inventory of the particular blood type, with the older blood being stored higher in the inventory list. When all these units have been inserted into the inventory list, the new list is still in order of date drawn (oldest first within blood type) regardless of the date the unit was received at the blood bank.

Returns of Called For Blood

Blood may be returned to the blood bank at any time during the day, but most of the returns come from the operating rooms, where the surgical refrigerators are emptied of all unused blood at the end of the day, which is returned to the blood bank. Returns from surgery are known to have been properly stored and are completely

acceptable to the blood bank. Other units which are returned to the blood bank during the day may be questioned as to their storage and would probably be put aside for a period of hours and tested to see if any evidence of improper storage resulted. The combination of these circumstances leads to the result that units which are received as returns at the blood bank are not available to another patient until the next day. For this reason, the simulator processes its returns at the end of the day, after all the day's demands have been satisfied, so that they will not be available until the next day.

The simulator determines which units are being returned on the current day by examining the inventory listing and finding all those units which have been declared temporarily unavailable; checking the return date (stored in the eighth data position) to see if it is the current date. If the unit is returned today, its status is restored to available, the reference to the previous reservation is erased, and the unit is again part of the regular inventory.

Cancellation of Reservations

The first thing done in the morning in the hospital blood bank, after removing out-dated blood, is the cancellation of reservations that have exceeded the specified time on reserve. In the simulator this task is performed the same way. It is accomplished immediately after the day counter is incremented to the next day, the out-dated blood having already been removed at the end of the preceding day. Those units whose reservations expire on this date are indicated as having not been called for by a blank in

their seventh data position and having the current date as the date the reservation expires (the date in the eighth position).

The simulator examines all units of blood on reserve and locates those still in inventory whose reservation expires today. For each of these units, the simulator eliminates all references to the current reservation, thus cancelling it. The unit again is made part of the regular inventory and is available to patients submitting requests today. The simulation then returns to the beginning of the program, ready to carry out another day's work.

Accumulation of Statistical Information

In addition to simulating the operations of the blood bank, the computer program also accumulates statistics on the operations being performed in the simulator. The following sections describe the types of data that are available from the simulation program.³⁰

Blood usage and wastage

Tallies are incremented each time a unit permanently leaves the inventory, either for transfusion or because it went out of date. At the end of the simulated time period, the program prints out the number of units processed, the number transfused, and the number and percent expired for each blood type.

Shortages of blood

When the simulator does not have enough blood in inventory

³⁰Examples of the available types of output are shown in Appendix VI.

to fill current requests for crossmatching, it accelerates the processing of the day's ordered blood and tries to satisfy the requests using this blood. When this happens, the computer program prints out a message to that effect at the time of the occurrence. If the simulator is still unable to satisfy all demands, it places emergency orders for the necessary units, assumes they arrive rapidly, and uses them to fill the requests. Every time an emergency order is placed, a message is printed out indicating the blood type and the number of units ordered at that time. Analysis of these messages therefore provides information on the frequency of shortages and their magnitude for any set of operating conditions.

Blood unit statistics

Whenever a unit of blood is crossmatched, called for, or returned, a tally is made of that event for the particular unit. Every time a unit of blood which was on reserve is taken off the reserve list either because it was called for or its reservation was cancelled, the length of time it spent on reserve is tallied for that unit of blood. When the unit leaves the blood bank, these tallies are accumulated into the appropriate output table. In addition, if the unit was transfused, the age when it was transfused is calculated and also tallied into an output table.

These tables accumulate all the information described above for all the units of blood processed by the simulator, by blood type, and they are printed out at the end of the simulation period. The tabulations of crossmatching performed and age

of blood at transfusion are especially important when comparing different operating policies which may affect the work load at the blood bank in terms of ~~cross~~matches or the "quality" of the transfused blood as measured by its age.

CHAPTER V

PROPOSED CHANGES IN OPERATING POLICIES AND THEIR IMPLEMENTATION IN THE SIMULATOR

Double-Crossmatching

When a unit of blood is put on reserve in a hospital blood bank, it is only available to the patient for whom it was reserved until that patient actually uses it or until the reservation expires. Thus, if the patient does not use the unit, it will simply remain in inventory, getting closer to going out of date. Even though there might be other patients to use it, they would be given younger units because all older ones were already on reserve.

The double-crossmatching method that is proposed here would allow each unit of blood to be available to two patients while on reserve. The unit, having been crossmatched against both patients' blood, would be compatible with both patients. It would be given to either patient for whom a requisition was submitted. This would be satisfactory if it were known that only one of the two patients would requisition blood. Since there is a reasonable chance that both patients will need a unit, this concept is unacceptable as no unit would be available for the second patient. If at the same time, a second unit was also crossmatched against both patients and was put on reserve, this unit could be used for the second patient.

This method would then put the same number of units on reserve as the existing reservation system. For example, if two people each requested one unit there would be a total of two units

put on reserve. The difference is that each of the two units would be available to either of the two patients instead of to only one particular patient.

The probability of a unit being used with the current reservation system may be denoted as p . In the current method, this is the probability that the first unit will be used. It is also the probability of the second unit being used. With the proposed double-crossmatching method, the first unit would be used if either one or both patients requisitioned the blood. Thus, the probability of using the first unit is equal to:

$$\begin{aligned} & p^2 + 2p(1-p) \\ &= p^2 + 2p - 2p^2 \\ &= 2p - p^2 \\ &= p(2-p) \end{aligned}$$

Since $0 < p < 1$, $p(2-p)$ is greater than p for all values of p , proving that the probability of using the first unit is increased. For example, if $p = \frac{1}{2}$, $p(2-p) = \frac{3}{4}$, yielding a 50 percent increase in the probability that the first unit would be used. The percentage increase gets larger as p gets smaller, with an upper bound of 100 percent gain.

On the other hand, the second unit would only be used if both patients requested their units. The probability of using the second unit is equal to p^2 which, since $0 < p < 1$, is less than p , resulting in less chance of using the second unit. The following table summarizes these probabilities:

TABLE 16
PROBABILITIES OF USING A UNIT
OF BLOOD ON RESERVE

Unit	Single Crossmatch	Double Crossmatch
First	p	$p(2-p)$
Second	p	p^2
Average	p	p

The double-crossmatch method does not increase the overall probability of usage. It achieves its goal by shifting some of the probability from the second unit to the first unit. This shifting of probability would do no good if both units were identical with respect to their chance of going out of date; that is, if they were both the same age, since the expected number of units used is exactly the same in both systems. If, however, the first unit were an "old" unit (close to going out of date) and the second unit could be arranged to be a "young" unit, this method would reduce the chance of the older unit going out of date while it increased the chance of the younger unit growing a little older. If this method of crossmatching is used, it should reduce the amount of blood that goes out of date since each unit's chances of usage would be increased as the unit got older.

Several difficulties arise in its application. First of all, it causes an increase in the amount of work to be performed at the blood bank. It would increase the existing crossmatching load by 100 percent if it were possible to perform a double-crossmatch for every request received at the blood bank. This

theoretical maximum is usually not reached, since requests for one patient must be matched with requests for a different patient. Matching two units requested for the same patient with one another would not achieve any gain whatsoever.

Secondly, as previously mentioned, for the double-crossmatching method to work, each patient must have an alternative unit available to him if the primary crossmatched unit has already been called for. Furthermore, one of these units should be "old" and the other should be "young". The implementation of the double-crossmatching policy thus requires a definition as to which units should be considered as old and which young. This is an arbitrary specification which might affect the capability of the double-crossmatching policy. When the ability to perform double-crossmatching was introduced into the blood bank inventory simulator, this definition was made part of the input parameters so that the effect of varying it could be evaluated.

Since the double-crossmatching policy does add considerably to the crossmatching workload, the ability to restrict double-crossmatching was also provided. This is accomplished by allowing only units that meet some criteria (e.g. older than x days) to be eligible for double-crossmatching. This permits determining if some (most) of the anticipated reduction in wastage could be obtained without the large increase in work that would accompany unrestricted double-crossmatching.

Implementation of Double-Crossmatching in the Simulator

Implementation of a double-crossmatching policy in a blood bank would require complete revision of the process of selecting units for crossmatching and subsequent reservation. Small but significant changes in the process of disbursing units to patients and cancelling reservations would also be needed. The following sections describe the changes made in the simulator to enable it to perform its functions while using a double-crossmatching system.

Crossmatching and reservation

Under the present reservation system, the rule for the selection of a unit to crossmatch against a patient's request is quite simple; use the oldest unit of the patient's blood type. In a double-crossmatch system, the major emphasis is to give the oldest units an increased chance of being used by crossmatching them against two different patients' requests. This is accomplished in the simulator by finding the oldest unit of blood which has already been crossmatched against another patient and is therefore on reserve. This unit will then also be available to the second patient if the primary patient does not request it. Another unit must be provided to satisfy this patient's request if the primary patient requests the original unit. The simulator finds this unit by examining the "young" units not on reserve and obtains one which is then also crossmatched against the current patient, who becomes the primary crossmatch. The other patient is also crossmatched against the "young" unit and would be the second patient for this unit.

After these crossmatches were performed the status of the two units in the blood bank can be seen in the following listing:

Unit of Blood	Primary Reservation	Secondary Reservation
"Old" Unit	Patient A	Patient B
"Young" Unit	Patient B	Patient A

If when searching for a unit to create a secondary reservation, one is not available among the "old" units of blood, because all those on reserve in this group already have a secondary reservation, then the simulator will try to find a "young" unit to use for a secondary reservation. It will then look for an "old" unit for which it will create the primary reservation. In this case, the double-crossmatching method is just as effective, except that the listing of reservations would be reversed as follows:

Unit of Blood	Primary Reservation	Secondary Reservation
"Old" Unit	Patient B	Patient A
"Young" Unit	Patient A	Patient B

In either case, when creating a second reservation, the program always looks first among the units of the alternative group for the primary crossmatch. If a primary crossmatch is not available among the units of that group, the simulator will create a primary crossmatch using any unreserved unit. Any available unit would be used, since it is absolutely imperative

that a primary as well as a secondary reservation be available should both patients send in requisitions for a unit of blood. If no secondary crossmatch is available, then the simulator proceeds as before, to try (oldest first) to find an unreserved unit for crossmatching and (primary) reservation.

As before, the information relating to the sequence of events occurring after each request must be appended to the unit of blood reserved for the requesting patient. In the double-crossmatching system each unit could be reserved for two patients, one primary and one secondary, and the simulator must keep track of which sequence of events applies to which request. Since each request must have a primary reservation, the information about what is to follow that request is only appended to the unit for which the patient is primary. The identification of the alternate unit is stored in the sixth data space of each unit on reserve and the information about the secondary patient (who is the primary patient for the alternative unit) is stored in the data locations associated with that unit. Thus, the simulation has access to the information relative to both reservations and can process them appropriately.

Restrictions on double-crossmatching

As just described, only lack of patients would prevent double-crossmatching being done for all requests for reservation of blood, as this method requires two patients for every pair of units that are double-crossmatched. Since it was also desired to determine if some double-crossmatching might still be effective,

the simulator was given a variety of conditions which could be specified before attempting double-crossmatch. These options are:

1. Double-crossmatch only against another unit that has has been made a primary reservation on the same day. This condition was included if practical considerations of operating a hospital blood bank requires such a stipulation, when it would be important to measure its impact.
2. Double-crossmatch only those units which are more than x days old. This condition permits the simulator to attempt double-crossmatching only when one of the two units which are to be paired is greater than some specified age. Its effect is to force increased attention to those units which have the greatest chance of being wasted and to cut down the work load by reducing the permissible number of double-crossmatchings.
3. Double-crossmatch only the oldest x percent of the units of each blood type. The effect of this condition is similar to the one stated above and was included as an alternative method of limiting the permissible crossmatches.
4. Double-crossmatch only the oldest x units of each type. This type of limitation is used to restrict the permissible double-crossmatches in the more prevalent blood types (e.g. A+, O+) while allowing

almost all the units of the rarer types to be double-crossmatched, since their total quantity in inventory would be less than the limiting quantity. For example, if the rule were to double-crossmatch only the oldest 20 units of each blood type, this would severely limit double-crossmatching to some 20-25 percent of the units in inventory for A+ or O+ blood, since between 80 and 100 units of each of these blood types are stocked. However, the total supply of blood types A-, B-, AB+, AB- and O- would normally be less than 20 units. This condition, therefore, would impose no additional restriction (other than the need of two patients) on these rarer blood types. The work load would still be considerably reduced since most of it is, of course, in the predominant types. The selectivity of its application is the primary goal.

Processing requisitions for blood

The fact that a unit of blood on reserve may be available to two patients instead of one does not, by itself, provide for a reduction in the number of units that go "out-of-date". It is necessary that the processing of the requisitions consider the double-crossmatching policy and disburse the appropriate unit in response to a patient's request. Since two patients are available to use each unit which has been double-crossmatched, it follows that each patient has two units from which the blood bank may

choose in filling his request. The basic disbursement policy for use in implementation of double-crossmatching is always to send out the older of the two units against which the patient has been crossmatched, regardless of whether he has the primary or secondary reservation. It is this policy that provides the increased probability of usage of the older unit. Of course, once the older unit has been disbursed, the other unit will remain on reserve, now available only to the second patient until (a) he calls for it, or (b) the reservation expires, or (c) another patient's request for crossmatch and reservation is processed and this unit is used as the younger unit in a new double-crossmatched pair.

In the simulator, the call for date (if any) has been inserted into the seventh data location for each unit of blood on reserve. This is the date that the primary patient is due to requisition a unit. If the location is blank it implies that the reserved will not be used and will be cancelled on the appropriate date. However, the alternate patient may have requisitioned the unit (if the primary patient did not) or the alternate requisition may arrive at the blood bank before the primary patient's requisition. To insure that the older of the pair of units is sent out in either case, the simulator checks each unit and determines if the primary patient has sent in a requisition. If so, the date in the call for location of this unit is the current date. If not, it then references the alternative unit for this patient (which is the primary unit for this unit's secondary

patient) and determines if this patient has sent in a requisition. In this case, the simulator interchanges the primary and secondary patients (the designation merely refers to whom was crossmatched first and has no other meaning) and their reservation sequences. Now, the unit has been requisitioned by the "new" primary patient and the call for is processed as in the current system.

The simulator checks each unit of blood in this manner until all units requisitioned on the current date are processed. As each unit disbursed is made unavailable to other patients, its alternate reservation is cancelled and the reference to the alternate unit is eliminated. The alternate unit remains on reserve, but is available only to the other patient who is now assigned the prime reservation.

Processing cancellations of reservations

In the standard crossmatching system, when a patient's reservation is cancelled, the unit of blood which was on reserve is made available for other patients' requests. In a double-crossmatching system, if one patient of a pair does not call for his reserved unit in the reservation period, his reservation must also be cancelled. In this case, however, there are two units of blood which were available to the patient. Thus, the patient's primary reservation as well as secondary reservation must be cancelled. If the reservation of these two units for the alternate patient is still in force, then the alternate patient will have two units available to him when only one is needed. It is

necessary, in this case, to keep the older unit on reserve for the alternate patient and to cancel the reservation of the other unit, so that it is made available to other patients.

In the simulator, the date a reservation is to be cancelled, if it has not been previously called for, is inserted into the eighth data location for each unit on reserve. If this date is the current day, the simulator checks if this unit has an alternate patient. The primary unit on reserve for the alternate patient is located and the simulator determines if its reservation expires on this date. If not, the simulator cancels both the primary and alternate units for the primary patient, retains the older of the two units as the primary reservation for the alternate patient, and eliminates all references to the younger unit.

Recognition of a "Special" Class of Patients

As a unit of blood gets older, the number of opportunities for it to be transfused is reduced. When a unit gets to be 18 or 20 days old, it may have only one or two possible reservations before it goes out of date. If there were some way of increasing the probability of the unit actually being used by the patient who reserves it, this would reduce the chance of older units being wasted. A cancellation or a return at this point in their age would probably not permit another crossmatching before they went out of date. There are two ways to increase the probability of usage of a particular reservation:

1. Increase the probability of usage by patients in general (i.e. to change the doctors' ordering policies so that they would not over-order as much), which is highly unlikely;
2. Find some patients whose usage patterns - probabilities of call for following request for reservation and probabilities of return if the unit was called for - were different from that of the overall patient population.

A statistical analysis of the conditional distributions of the number of units requisitioned for a given number of units reserved and the conditional distributions of the number of units returned for a given number of units requisitioned was made for each of a variety of patient classifications (e.g., blood type, private, semi-private, ward, diagnosis, etc.) to determine if any patient subgroup had desired characteristics. Two patient types were found with usage rates significantly different from the general hospital patient population: anemia patients and out-patients. These patients have much higher probabilities of calling for reserved units than do other patients. They also have much lower return probabilities so that the chances that a reservation for one of these patients will result in a transfusion is much higher than the overall average. The conditional distributions of requisition and of return for these patients are given in the tables below and they can be compared with the overall figures given in the previous chapter.

TABLE 17
 CONDITIONAL DISTRIBUTION OF NUMBER OF UNITS
 REQUISITIONED FOR DIFFERENT NUMBERS
 OF UNITS RESERVED FOR
 "SPECIAL" USERS

Number Called For	Number of Units Reserved					
	1	2	3	4	5	6
0	9.8%	13.6%	5.9%	3.3%	0.0%	0.0%
1	90.2	10.2	11.8	16.7	0.0	0.0
2		76.2	5.8	30.0	0.0	0.0
3			76.5	10.0	0.0	0.0
4				40.0	0.0	25.0
5					100.0	0.0
6						75.0
Mean (units)	0.90	1.63	2.53	2.67	5.00	5.50

TABLE 18
 CONDITIONAL DISTRIBUTION OF NUMBER OF UNITS
 RETURNED FOR DIFFERENT NUMBERS
 OF UNITS REQUISITIONED
 FOR "SPECIAL" USERS

Number of Returns	Number of Units Called For					
	1	2	3	4	5	6
0	97.8%	93.9%	85.7%	100.0%	100.0%	100.0%
1	2.2	4.4	7.2	0.0	0.0	0.0
2		1.7	0.0	0.0	0.0	0.0
3			7.1	0.0	0.0	0.0
Mean (units)	.02	.08	.29	.00	.00	.00

These patients are identifiable by information on their request slips. The blood bank can therefore separate their requests for reservation of blood and can crossmatch the oldest available units against these requests. This policy results in

the desired higher probability of usage of the oldest units of blood by making them available to patients more likely to use them.

One problem with supplying "special" users is that the same reason that gives rise to their higher probability of use also, in many cases, acts against their being transfused with older blood. In fact, many of their physicians will specifically request that the blood bank try to reserve units less than 14 (or some other specified) days of age. The statistical analysis of the data revealed that approximately 8 percent of the patients reserving blood are in those two classes, but it is anticipated that not all of these patients could be given the oldest units of blood. A 5 percent estimate was used to measure the effectiveness of this policy. Although this estimate may not be accurate, it is believed to be adequate to establish the capability of this approach. The figure could be varied to determine effectiveness if there were more or fewer patients who could be identified as "special users", eligible for the oldest units of blood.

Implementation of the "Special" User Policy in the Model

To implement this policy the simulator must first create identifiable patients who can be considered special users. It does this by randomly assigning¹ some of the patients to this class when patients are generated and by modifying their identification when the crossmatching and reservations are made. The

¹Bernoulli trials, discussed in Appendix X, were used to make the assignment.

percent of patients who are classified as "special" by the simulator is defined in the input to the program. This can be varied from the 5 percent that was used in the test cases. A cross-matching date is assigned to these patients exactly as to all other patients and the requests are put in the list of cross-matches to be performed.

Because ~~the~~ special users are to be assigned the oldest units of unreserved blood, the simulator will try to cross-match requests for these patients first on the day they were scheduled for crossmatching. Since the selection of units for crossmatching and reservation is done in age order (oldest first), this method results in reserving the oldest unit blood of each type for the special patients, providing there were special patients on that day. Just before the unit of blood in inventory is selected, the simulator assigns an event sequence to the request which will determine what will happen to the unit cross-matched for it. This event sequence is also generated for the special patient requests in the same manner as for all patients. However, probabilities of calling for and returning the units reserved are used that describe these patients' usage characteristics rather than the usage patterns of the overall patient population. Once the event sequence is assigned and the unit is put on reserve for the patient, the processing of subsequent occurrences is performed exactly the same as it is for every other reservation in the simulated blood bank.

Use of "Old" Rh Negative Blood
for Rh Positive Patients
of the Same
Blood Group

Although Rh positive blood cannot be transfused into Rh negative people except in special circumstances, there is no medical reason why Rh negative blood cannot be transfused into Rh positive blood and it is therefore deemed desirable to preserve those units for patients who must have them. Since these blood types are rarer, the demand level for them is much lower. The wastage rate is therefore much higher since hospital blood banks consider it imperative to maintain sufficient inventory to satisfy demands that might arise and to limit the shortages that occur.

However, it would be advantageous if Rh negative blood which would have gone out of date anyway could be used for an Rh positive patient. Rh negative blood, which has reached the limit of its life and for which there is no Rh negative patient, could be reserved for an Rh positive patient without incurring any penalty. But this would give the unit only one chance and if that patient did not use it, it would still be wasted. It might be desirable to allow the use of Rh negative blood for Rh positive patients while it still had a few days of life left, so that it would have more than one chance of being used. In such a case, it is possible that an Rh negative patient might request blood before the unit had expired and could therefore have used that unit. As the unit would no longer be available, another unit of Rh negative blood would be used for the patient.

This will not increase the chance of not having a unit for the Rh negative patient since the blood bank would still maintain its inventory levels. It would mean that extra units of the rarer Rh negative blood would have to be ordered from the central sources to compensate for those units which were given to Rh positive patients but could have been used for Rh negative patients.

It was decided to investigate the operation of a policy which made Rh negative blood older than x days of age (x being specified in the input, to measure the effect of different age levels) available to Rh positive patients if there were no Rh negative patients available at that time. To evaluate the effectiveness of this policy, it is necessary to compare the number of units of Rh negative blood which were used and which otherwise would have gone out of date with the number of extra units of Rh negative blood that had to be ordered, since some of the blood given to Rh positive patients might have been available for Rh negative patients before it expired. This kind of evaluation is possible with the simulator by comparing a pair of cases which are identical except that one has this capability and one does not.

Implementation of the Use of Rh Negative Blood for Rh Positive Patients in the Simulator

The availability of Rh negative blood older than x days of age to Rh positive patients is made possible in the simulator by slightly modifying the order in which it performs the cross-matching and reservation work contained in the worklist. The

simulator first makes sure that all requests for crossmatching and reservation for Rh negative patients have been performed before allowing any Rh negative blood to be used for Rh positive patients on that day. The requests from Rh positive patients are then processed. Assured that all requests for Rh negative blood have been honored, the simulator checks the Rh negative inventory of the same blood group as the Rh positive patient to see if there is any available (unreserved) blood that is older than x days of age. If such blood is available, the oldest unit is crossmatched and reserved for the Rh positive patient. If not, the simulator follows the normal course of action by finding the oldest available unit of blood in the patient's correct blood class. This procedure is followed for all requests for Rh positive patients until all the Rh negative units in the same blood group older than x days of age have been reserved. The assignment of the sequence of events to occur for this reservation and the subsequent processing of those events is not affected by the way the unit was originally assigned to a patient's request.

When this capability is used in conjunction with the double-crossmatching procedure certain restrictions are imposed upon the simulator to insure that a unit of Rh positive blood is not used for an Rh negative patient. These restrictions limit the double-crossmatching of Rh negative blood to those cases where both patients are Rh negative or Rh positive.

CHAPTER VI

RESULTS OF USING THE SIMULATION MODEL

Validity of the Model

Use of the simulator under existing operating rules

The basic statistical test of a simulation model is its ability to reproduce the operational results of presently used procedures when it is run under the existing conditions. The major concern in this statistical validity test is the ability of the simulator to show shortage and wastage levels which are comparable to those achieved in the real system. Accordingly, the simulator was run using the present crossmatching policy and desired inventory levels reflecting those in use at Mount Sinai Hospital during the study period. The following results were obtained for six months of simulated time.

TABLE 19
RESULTS OF SIMULATION OF MOUNT SINAI
HOSPITAL BLOOD BANK FOR
A SIX-MONTH PERIOD

Blood Type	Inv. Level	Short-age Situations	Units Trnsfcd	Units Wasted	Units Processed	Percent Waste
A+	80	0	1506	151	1657	9.11
A-	12	6	173	26	199	13.07
B+	38	3	510	112	622	18.01
B-	5	2	27	29	56	51.79
AB+	17	3	232	21	253	8.30
AB-	3	3	13	15	28	53.57
O+	100	1	1859	161	2020	7.97
O-	13	3	191	28	219	13.57
6 Month Total		21	4511	543	5054	10.74
Year Estimate		42	9022 ^a	1086	10108	10.74

^aSee footnote b, Table 20, page 111.

Unfortunately, no information on actual blood wastage by blood type was available from the hospital, as existing records are kept only on total losses. The statistical comparison can, therefore, be made only on the basis of overall results. The following table shows the wastage caused by blood going out of date for the years 1967-1968:

TABLE 20
MOUNT SINAI HOSPITAL BLOOD BANK
ACTUAL WASTAGE, 1967-1968^a

Year	Number Transfused	No. of Units Out of Date	No. of Units Processed	Percent Waste
1967	10697	1270	11967	10.61
1968	11393	1471	12864	11.43
Total	22090	2741	34831	
Avg. Year	11045 ^b	1370	12415	11.04

^aMonthly Blood Bank Reports; Mount Sinai Hospital, January 1967-December 1968.

^bThe difference between the simulated number of transfusions and the actual number of transfusions is due to the elimination of transfusions for Open Heart Surgery from the simulation and these run about 2000 per year.

A test of significance between two proportions was performed to determine whether the simulation wastage and the hospital wastage were significantly different. The test has the following form:

$$Z = \frac{p_1 - p_2}{\sqrt{p_1 - p_2}}$$

where Z = a normal deviate to be compared with the critical value of 1.96 for a test at the significance level for $\alpha = .05$;

p_1 = the observed hospital proportion wasted;

p_2 = the simulated proportion wasted;

$S_{p_1-p_2}$ = the standard error of the difference between two percents which is

$$\sqrt{\bar{p}\bar{q}\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$$

where $\bar{p}$ is the best estimate of the true proportion wasted under the null hypotheses that both p_1 and p_2 are sample estimates of a common P (true proportion wasted) and $\bar{q} = 1 - \bar{p}$.

$$\text{Thus } \bar{p} = \frac{2741 + 543}{24831 + 5054} = 10.99\%$$

$$S_{p_1-p_2} = \sqrt{.1099 \times .8901 \times \left(\frac{1}{24831} + \frac{1}{5054}\right)}$$

$$= \sqrt{.0000233257}$$

$$= .00483$$

$$\text{and } Z = \frac{.1104 - .1074}{.00483}$$

$$= \frac{.0030}{.00483}$$

$$= 0.62$$

Since 0.62 is less than the critical value of 1.96 there is no reason to reject the null hypothesis that the observed and simulated percent waste are not different.

While it was not possible to obtain estimates of actual waste by blood type, discussions with the blood bank personnel indicated that the wastage of Rh negative blood was about twice that of Rh positive blood. These results were also observed in the simulated output, as illustrated in the following table:

TABLE 21

SIX-MONTH SIMULATED RESULTS
COMPARISON OF WASTAGE:
Rh POSITIVE vs. Rh NEGATIVE BLOOD

Blood Type	Number Transfused	No. of Units Out of Date	No. of Units Processed	Percent Waste
Positive Rh	4107	445	4552	9.78
Negative Rh	404	98	502	19.52
Total	4511	543	5054	10.74

It is difficult to evaluate the number of shortage situations encountered in the simulated six-month (26 weeks) period. No hospital records are kept on the number of special orders placed with central sources when the hospital blood bank inventory level is drawn too low to last until the next standard ordering time. Discussion with the chief technician in charge of replenishing inventory did not yield a better estimate of its occurrence than "less than once a week". While not a precise estimate, it can be compared with the simulated shortages, of which 21 occurred in a 26-week period. Thus, the simulator, when using inventory levels similar to those applied in the hospital blood bank, also incurs shortage situations that cannot be considered different from the general estimate of occurrences in the blood bank.

Use of the simulator to demonstrate the effect of changing the inventory level

Previous researchers have done extensive work on the relationship between desired inventory level and the wastage and shortages that occur in the blood bank. The simulator was run using several different inventory levels to verify that the

simulated output would be affected by different desired inventory levels. As expected, the simulated results with respect to shortages and wastage, exhibited the relationship previously reported; that is, as the desired level is raised, shortages decrease and wastage increases and as the desired level is lowered, shortages increase and wastage decreases. The following table illustrates the occurrence of this relationship for each of the blood types:

TABLE 22
RELATIONSHIP BETWEEN SHORTAGES AND WASTAGE
FOR DIFFERENT INVENTORY LEVELS
BY BLOOD TYPES

Blood Type	Inventory Level (units)	Percent Waste	No of Days Req'ng. "Emergency" Orders
A+	60	7.72	33
	70	8.68	7
	80	9.11	0
A-	10	10.82	14
	12	13.07	6
	14	14.78	3
B+	30	13.41	12
	35	16.53	4
	40	19.43	1
B-	3	44.90	9
	4	49.06	3
	5	51.78	2
AB+	13	4.13	11
	15	6.45	8
	17	8.30	3
AB-	2	50.00	7
	3	58.06	3
	4	65.79	0
O+	80	6.58	15
	90	6.91	3
	100	7.97	1
O-	12	11.77	8
	13	12.79	4
	14	14.35	0

Source: Simulated results for six-month periods.

As can be seen in the above table, the expected relationship occurs for each blood type. Moreover, the effect of changing inventory level on percent wastage relative to the change in shortages is directly related to the relative occurrence of the particular blood type. The rarer the blood type, the greater the effect on wastage relative to shortages and the more predominant the blood type, the smaller the effect on wastage relative to shortages. This can be seen by comparing the slopes of the curves for different blood types as shown in Figure 11.

Construction of the simulation model as a criterion of validity

The ultimate test of a model's validity is not its ability to reproduce existing results. The model is designed to investigate new operating procedures which cannot be verified in the real situation. The real measure of its validity is the manner in which it represents the true situation. In this regard, the simulation model that has been created represents each aspect of the operation of a blood bank in a realistic manner so as not to introduce any bias in its performance. The procedures used in the simulator to accomplish the operations performed by blood bank personnel were discussed with the Director of the Mount Sinai Hospital Blood Bank and he agreed that the simulator was a good representation of its operation. The quality of this representation offers the most assurance that the results obtained by the simulation model truly reflect the operational levels that would be achieved in the blood bank, if the policies under

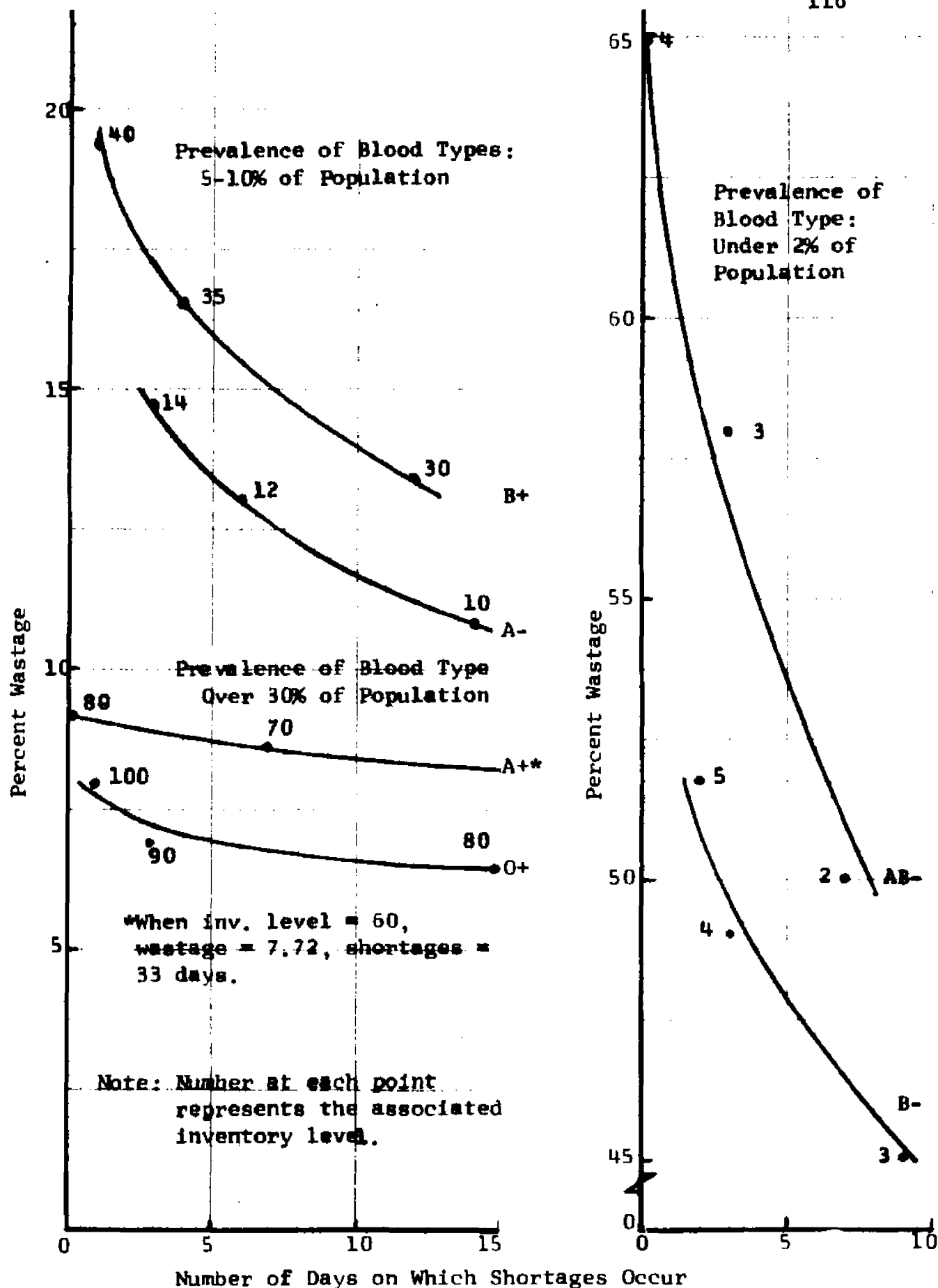


Fig. 11.--Relationship between shortages and wastage for different desired inventory levels for selected blood types.

Source: Table 22.

investigation were used.

Effect of the Proposed Policy Changes
on the Level of Shortages

The first experiments performed using the simulation model were some basic cases to determine the effect of the three proposed policy changes on the level of shortages and the percent wastage. In this section the effect of the changes on the shortage level is examined to see if the previously observed inverse relationship between shortages and wastage is also applicable to these policy changes.

A statistical experiment was designed to investigate the effect of the three proposed policy changes. The experimental design used is known as a 2^3 factorial experiment, which enables the investigation of the effect of three factors (the three proposed changes) at two operational levels (in this case either in effect or not in effect). The eight experimental cases are described in the following table:

TABLE 23
EXPERIMENTAL DESIGN ARRANGEMENT

Case Number	Levels of the Factors			Treatment Combination
	(A) Double-Crossmatching	(B) "Old" Neg. Blood to Pos. Patients ^a	(C) Special Users	
1	No	No	No	(1)
2	Yes	No	No	a
3	No	Yes	No	b
4	Yes	Yes	No	ab
5	No	No	Yes	c
6	Yes	No	Yes	ac
7	No	Yes	Yes	bc
8	Yes	Yes	Yes	abc

^aIn this experiment Rh negative blood at least 18 days old was considered to be "old" blood.

This design provides an efficient method of estimating the effect on shortages of each of the three factors as well as the interactions (if any) among the factors. The shortage data collected for the running of the experimental design were analysed. Yates Method was used to obtain the sums of squares for the analysis of variance.

The results of this analysis can now be interpreted to determine the effect of each of the policy changes on the number of shortages incurred by the blood bank.

Double-crossmatching

The four runs using double-crossmatching gave rise to a total of 79 shortage situations over an effective period of 2 years of simulated time (4 runs of 6 months each), or an average of 19.75 shortage situations per run. The four matching runs, except for the use of standard crossmatching, gave rise to a total of 80 shortage situations over the 2 years of simulated time or an average of 20 shortages per run. The difference between the totals (79-80) is shown in the contrast column of Table 24a of Yates Method in the row associated with the crossmatching factor (treatment combination a). The difference between the two averages (19.75 - 20.00) is shown in the same row in the effect column. The sums of squares and mean square deviation associated with this difference is shown in the Analysis of Variance table and the F test for the significance of this difference indicated that the use of double-crossmatching has no effect on the number of shortages that are incurred.

TABLE 24

ANALYSIS OF SHORTAGES

Table 24a.--Yates Method for a 2^3 Factorial Design^a

Case No.	Treat- ment Combin- ation	Response - No. of Shortage Situations	(I)	(II)	Contrast (III)	Effect (III)/4	S.S. ₂ (III) ² /8
1	(1)	21	43	90	159	---	---
2	a	22	47	69	- 1	-0.25	0.125
3	b	24	33	0	7	1.75	6.125
4	ab	23	36	-1	- 5	-1.25	3.125
5	c	16	1	4	-21	-5.25	55.125
6	ac	17	-1	3	- 1	-0.25	0.125
7	bc	19	1	-2	- 1	-0.25	0.125
8	abc	17	-2	-3	- 1	-0.25	0.125

^aC. R. Hicks, Fundamental Concepts in the Design of Experiments, Holt, Rinehart and Winston, 1964, pp. 102, 106.

Table 24b.--Analysis of Variance
(Pooling all Interactions)^b

Source	d.f	S.S.	M.S.D.	F Ratio	Sig. ($\alpha = .05$)
Double-Crossmatching (A)	1	0.125	0.125	0.143	N.S.
"Old" Rh negative blood to Rh positive patients (B)	1	6.125	6.125	7.000	N.S.
"Special" Users (C)	1	55.125	55.125	63.000	Sig.
Error (Pooled Interactions)	4	3.500	0.875	---	--
Total	7	64.875			

^bThe three factor interaction was used as an estimate of error to test the two factor interactions. When none of these was significant, all the interactions were pooled to provide a better estimate of error variation with 4 degrees of freedom, to increase the power of the tests of the main effects.

"Old" Rh negative blood to
Rh positive patients

The four cases allowing "old" Rh negative blood to be transfused to patients having Rh positive blood showed a total of 83 shortage situations over an effective period of 2 years. The four comparable cases without this capability gave rise to a total of 76 shortages. There were a total of only 7 more shortages in two years using this capability, or an average increase of 1.75 shortages per six-month period. The difference between the total number of shortages (83-76) is shown in the contrast column of the table of Yates Method in the row associated with this factor (treatment combination b). The difference between the average number of shortages per six-month period (20.75 vs. 19.00) is shown in the same row of the Yates Table in the effect column. The sums of squares and mean square deviation associated with this difference is given in the Analysis of Variance table and the F test indicated that this difference is not significant at the $\alpha = .05$ level. Therefore, allowing the use of "old" Rh negative blood for Rh positive patients does not have a significant effect on the level of shortages incurred in running a blood bank.

Recognition of "special" users

The four cases which recognized the existence of those patients who have a higher probability of using the blood they

had reserved incurred a total of 69 shortages over the effective period of two years. The four cases which were run without recognition of these users had a total of 90 shortage situations over the same total of two years of simulated time. This reduction of 21 shortages over the four cases is equivalent to having 5.25 less shortages ($22.50 - 17.25$) in a six-month period, or almost one less shortage situation a month. The difference in total shortages and the average difference per six-month run are shown in the contrast and the effect columns of the Yates Method Table in the row associated with the recognition of "special" users (treatment combination c). The sums of squares and mean square deviation associated with this difference is given in the Analysis of Variance table. The F test indicates that a significant reduction in the number of shortages is obtained when recognizing "special" users over that obtained when this option is not used.

Conclusion - Effect of policies on shortages

The analyses performed in the preceding sections on the effect of the three proposed policy changes on shortages indicate double-crossmatching and the use of "old" Rh negative blood for Rh positive patients have no appreciable effect on the level of shortages. This means that the effect of these policies on wastage

can be evaluated without considering any "trade-off" against shortages. Moreover, the analysis also indicated that the recognition of "special" users resulted in a significant decline in the number of shortages that occurred in the simulated blood bank. While the effect of this policy on the wastage level will also be considered independently of shortages, this reduction in shortages can be considered as an additional benefit over and above any savings in wastage.

Effect of the Proposed Policy Changes
on the Level of Wastage

Having established that the level of shortages in a blood bank will not be detrimentally affected by any of the three proposed policies, it was possible to study separately the effect of these policies on wastage. The current inventory levels were used so that the occurrences of shortages will be at an acceptable level as previously reported, or slightly lower. The same eight cases were then used to determine if the proposed policies would reduce wastage. In other words, the desired inventory level policy, of all those discussed, seems to be the crucial determinant of the shortage level. Having set inventory levels that will not give rise to an excessive number of shortages, the other three policies can be examined to determine if wastage levels can be reduced, with the knowledge that they will not increase shortages.

Since the frequency of patient arrivals is an important factor in the ability to perform a double-crossmatch, it is expected that the effect of implementing double-crossmatching will be different for the more predominant Rh positive blood types than for the rarer Rh negative types. In addition, the policy of using "old" Rh negative blood for patients having Rh positive blood is intended solely to reduce the wastage of Rh negative blood, while desiring that wastage of the more prevalent Rh positive blood groups will not be detrimentally affected. Accordingly, it was considered necessary to analyze the effect of these policies on the Rh positive and Rh negative blood types separately. Instead of cumulating the wastage over all blood types, it was obtained for the four Rh positive groups and for the four Rh negative groups separately. The two sets of data from the eight experiments previously discussed were then analyzed to determine the effects of the three policies on the wastage of Rh negative blood and Rh positive blood as well as interactions (if any) among the factors. Yates Method was again used to determine the effects associated with the treatment combinations.

The effects of the proposed policies on wastage were more likely to result in a relative reduction in percent wastage than an absolute reduction in the percent wastage. In this case, the effect of the policies is said to be multiplicative rather than

linear. Since the analysis of variance procedure requires the assumption of linearity of effects it was necessary to take the logarithms of the percent waste before performing the analysis since the logarithmic transformation will linearize a multiplicative relationship. The analyses were then performed on the transformed data and the results are shown in Table 25 and Table 26.

The results of these analyses can now be interpreted to determine the effect of each of the policy changes on the wastage of Rh positive and Rh negative blood in a hospital blood bank.

Double-crossmatching

When double-crossmatching is the only policy change made from existing procedure, the effect is to reduce wastage of Rh positive blood from approximately 9.7 percent to approximately 4.9 percent, a reduction of about 50 percent from the existing wastage level. If a blood bank is to make use of the "special" user policy but is using the standard crossmatching procedure and then switches to double-crossmatching, the result will be a reduction in wastage from about 6.4 percent to about 3.0 percent which is more than a 50 percent reduction in percent wastage. The above results will be true whether or not the blood bank is using "old" Rh negative blood for Rh positive patients, since this policy

TABLE 25

ANALYSIS OF WASTE FOR Rh POSITIVE BLOOD

Table 25a.--Yates Method for a 2^3 Factorial Design

Case No.	Trtmnt Comb.	Pct. Waste	Response $\ln(\text{Pct. Waste})$	(I)	(II)	Contrast (III)	S.S. $(\text{III})^2/8$
1	(1)	9.78	2.28	3.84	7.72	13.59	---
2	a	4.75	1.56	3.88	5.87	2.91	1.0585
3	b	9.69	2.27	2.87	1.38	-0.17	.00361
4	ab	5.00	1.61	3.00	1.53	0.15	.00281
5	c	6.30	1.84	0.72	-0.04	1.85	.4278
6	ab	2.80	1.03	0.66	-0.13	-0.15	.00281
7	bc	6.43	1.86	0.81	0.06	0.09	.00101
8	abc	3.12	1.14	0.72	0.09	-0.03	.00011

Table 25b.--Analysis of Variance
(Pooling all Interactions)^a

Source	d.f.	S.S.	M.S.D.	F Ratio	Sig. ($\alpha=.05$)
Double-Crossmatching (A)	1	1.0585	1.0585	628.2	Sig.
"Old" Rh negative blood to Rh positive patients (B)	1	.00361	.00361	2.14	N.S.
"Special" Users (C)	1	.4278	.4278	255.1	Sig.
Error (Pooled Interactions)	4	.00674	.001685	---	---
Total	7	1.49665			

^aThe three factor interaction was used as an estimate of error to test the two factor interactions. When none of these was significant, all the interactions were pooled to provide a better estimate of error variation with 4 degrees of freedom, to increase the power of the tests of the main effects.

TABLE 26

ANALYSIS OF WASTE FOR Rh NEGATIVE BLOOD

Table 26a.--Yates Method for a 2^3 Factorial Design

Case No.	Trtmnt Comb.	Pct. Waste	Response $\ln(\text{Pct. Waste})$	(I)	(II)	Contrast (III)	S.S. $(\text{III})^2/8$
1	(1)	19.52	2.97	5.75	10.34	19.85	---
2	a	16.15	2.78	4.59	9.51	2.07	0.5356
3	b	15.12	2.71	5.48	1.02	2.61	0.8515
4	ab	6.56	1.88	4.03	1.05	1.37	0.2346
5	c	16.80	2.82	0.19	1.16	0.83	0.08736
6	ac	14.03	2.66	0.83	1.45	0.03	0.00011
7	bc	11.71	2.46	0.16	0.64	0.29	0.01051
8	abc	4.80	1.57	0.89	0.73	0.09	0.00101

Table 26b.--Analysis of Variance
(Pooling Non-significant Interactions)^a

Source	d.f.	S.S.	M.S.D.	F Ratio	Sig. ($\alpha=.05$)
Double-Crossmatching (A)	1	.5356	.5356	138.1	Sig.
"Old" Rh negative blood to Rh positive patients (B)	1	.8515	.8515	219.6	Sig.
"Special" Users (C)	1	.08736	.08736	22.53	Sig.
AB Interaction	1	.2346	.2346	60.51	Sig.
Error (Pooled Interactions)	3	.01163	.003877	---	---
Total	7	1.72069			

^aThe three factor interaction was used as an estimate of error to test the two factor interactions. When two of these were not significant, these interactions were pooled with the three factor interaction to provide a better estimate of error variation with 3 degrees of freedom, to increase the power of the tests of the main effects.

does not have a noticeable effect on the wastage of Rh positive blood. These reductions were shown to be the major source of variation in the Analysis of Variance table for Rh positive blood. This variation was highly significant, thus demonstrating the large contribution that double-crossmatching can make in reducing the wastage of the more prevalent Rh positive blood.

The effect of double-crossmatching on the wastage of Rh negative blood is not as great as its effect on Rh positive blood wastage. When double-crossmatching is the only policy change made, its effect is to reduce wastage from about 19.5 percent to about 16.2 percent which is about a one-sixth reduction in waste. When double-crossmatching is employed in addition to recognition of special users, its effect is to reduce wastage from about 16.8 percent to about 14.0 percent which is also a reduction of about one-sixth. However, if double-crossmatching is used in conjunction with the use of "old" Rh negative blood for Rh positive patients, then it will reduce wastage of Rh negative blood from about 15.1 percent to 6.6 percent (no special users) and from 11.7 percent to 4.8 percent (with special users). These represent reductions of more than 50 percent, which shows much larger benefits from double-crossmatching of Rh negative blood when used in conjunction with the ability to give Rh negative blood to Rh positive patients than when it is used without the second policy.

These results are also exhibited in the Analysis of Variance table for Rh negative blood. The effect of double-crossmatching, while not as large as for Rh positive blood, is still highly significant. In addition, the analysis shows a significant interaction between double-crossmatching and use of "old" Rh negative blood for Rh positive patients. This means that the combination of these two factors gives rise to a savings which is greater than that which would have been expected by the simple addition of the savings achieved by either method. Double-crossmatching achieved approximately 17 percent savings by itself, and the other policy achieved (as will be shown later) about 25 percent savings. Thus, even if the methods were mutually exclusive (i.e., units saved by one method could not have been saved by the other and vice versa) which they are not, the total expected savings would be about 42 percent, yet the combination of the two policies resulted in a savings of about 57 percent. This indicates that some of the double-crossmatching benefit for Rh positive blood becomes available to Rh negative blood when Rh positive patients are permitted to use the "old" Rh negative blood.

"Old" Rh negative blood to Rh positive patients

The use of this policy is intended to reduce the wastage of Rh negative blood while not increasing the wastage of Rh positive

blood, even though some positive demand will be transferred to Rh negative blood, because of the much higher demand rate for Rh positive blood. Waste levels of both Rh negative and Rh positive blood groups therefore have to be examined to evaluate the effectiveness of this policy.

The effect of applying this policy on the wastage of Rh positive blood is shown in the following table:

TABLE 27

USE OF "OLD" Rh NEGATIVE BLOOD FOR Rh
POSITIVE PATIENTS - EFFECT ON
WASTAGE OF Rh POSITIVE BLOOD

Other Policies in Operation	Not Used	Used
No other policies	9.8%	9.7%
Double-crossmatching	4.8	5.0
"Special" users	6.3	6.4
Double-crossmatching and "special" users	2.8	3.1
Average	5.9%	6.0%

As can be seen from the above table, this policy does not materially increase the wastage of Rh positive blood, which is the desired result. This is further verified in the analysis of variance of Rh positive blood where it was shown that the effect on wastage of using "old" Rh negative blood for Rh positive patients is not significant.

Having achieved the desired result for Rh positive blood, it is now necessary to see if the policy reduces the wastage of Rh negative blood. When this policy was employed by itself, it reduced wastage of Rh negative blood from 19.5 percent to 15.1 percent. When it was used in conjunction with the "special" user policy, it reduced wastage from 16.8 percent to 11.7 percent. These savings represent reductions of about 25 percent in the level of Rh negative blood wastage. These reductions were shown to be the most important source of waste reduction for Rh negative blood in the analysis of variance previously performed and was highly significant.

As previously discussed, when this policy was used in conjunction with the double-crossmatching policy, the reduction of waste achieved by the combination exceeded the total of the individual reductions. This synergistic effect produced a reduction of more than 55 percent in the wastage of Rh negative blood. This "extra" saving appears in the Analysis of Variance table as an interaction between the two policies and its effect was significant when tested.

Recognition of "special" users

The ability to identify a class of patients with a higher probability of using the units of blood that have been reserved

for them than for average patients should result in a large reduction in wastage. Once identified, requests from these patients would be crossmatched against the oldest units of the patients' types to enhance the probability of using the old units before they go out of date. Analysis of the experimental results, comparing the cases with this capability to those without it, showed that this does indeed reduce the wastage of both Rh positive and Rh negative blood. The results of the experimental cases are shown in Table 28.

Table 28 illustrates that the addition of the ability to recognize "special" users and to reserve "old" blood for them will result in a reasonably consistent reduction in waste over the level achieved without use of this policy. This ability resulted in a reduction of more than one-third in wastage of Rh positive blood and a reduction of more than one-sixth in wastage of Rh negative blood. It is believed that the smaller saving of Rh negative blood was caused by the scarcity of "special" users among the rarer blood types, which limits the blood bank's ability to capitalize on the policy.

The observed reductions in wastage were quite large and the statistical analysis of that wastage demonstrated that the reductions in wastages for both Rh positive and Rh negative blood types represented significant savings.

TABLE 28
RECOGNITION OF "SPECIAL" USERS

Other Operating Policies	No "Special" Users	"Special" Users	Reduction in Waste
Effect on Wastage of Rh Positive Blood			
None	9.8%	6.3%	36%
Double- Crossmatching	4.8	2.8	41
"Old" Rh Nega- tive Blood to Rh Positive Patients	9.7	6.4	34
Double- Crossmatching and "Old" Rh Negative Blood to Rh Positive Patients	5.0	3.1	38
Average	7.4%	4.7%	37%
Effect on Wastage of Rh Negative Blood			
None	19.5%	16.8%	14%
Double- Crossmatching	16.2	14.0	13
"Old" Rh Nega- tive Blood to Rh Positive Patients	15.1	11.7	23
Double- Crossmatching and "Old" Rh Negative Blood to Rh Positive Patients	6.6	4.8	27
Average	14.4%	11.8%	18%

Summary of the effects of the
proposed policies on wastage

Previous analysis indicated that the proposed policies would not have a detrimental effect on the level of shortages (one policy might even reduce the number of shortages). The analysis of the effect of the policies on wastage demonstrated that all three policies have the desired effect. Double-crossmatching and the recognition of "special" users reduce wastage of both Rh positive blood as well as Rh negative blood although the savings is about twice as large for Rh positive blood because the applicability of these policies to Rh negative patients is limited by the relative scarcity of patients. The double-crossmatching policy requires a second patient to submit a request either on the same day as another patient or while another patient's reservation is in effect in order to create a double-crossmatch. This requirement necessarily limits its applicability in those blood types where requests are relatively infrequent. Similarly, if patients in general arrive rather infrequently, then the arrival of a "special" patient is even more infrequent. The few occurrences that happen cannot effect the large reduction in wastage that would be possible if many "special" users were available to crossmatch against the oldest units of blood.

The use of "old" Rh negative blood for patients having

Rh positive blood does not cause any increase in the wastage of Rh positive blood, while resulting in a significant reduction in the wastage of Rh negative blood. This desired outcome results from the greater demand for Rh positive blood which is still sufficient to prevent any "old" Rh positive units from being unreserved for any long period and going out of date, as happens to units of the Rh negative blood groups.

While these policies seem to provide benefits without any shortcomings, this is, in fact, not true. The next sections of this chapter will discuss the negative considerations of each of the proposed policies which must be "balanced" against their benefits to obtain a true evaluation of them.¹

Double-Crossmatching and Workload

If a double-crossmatch is to be achieved when using this policy, four crossmatches have to be performed to achieve double-reservations for requests from two patients (unit 1 against patient A,

¹While blood less than 21 days of age is considered in this study to be equally valuable, double-crossmatching does have an effect on the age of transfused blood. The objective of double-crossmatching is to increase the probability of using older units of blood before they go out of date. To the extent that this objective is achieved, increased quantities of older blood will be transfused, thereby raising the average age of the transfused blood. In the simulated cases, the average age of transfused Rh positive blood was increased by about 3/4 of a day and the average age of transfused Rh negative blood was increased by slightly under 1 day.

If, instead of comparing age of transfused blood, age of

unit 1 against patient B, unit 2 against patient A, unit 2 against patient B) whereas in the standard procedure only two crossmatches (unit 1 for patient A, unit 2 for patient B) would be performed. Were double-crossmatches possible for every pair of requests made of the blood bank, it would lead to a doubling of the amount of work associated with crossmatching. Since the conditions required for double-crossmatching are not always met, the theoretical maximum increase in work is not achieved. However, the use of double-crossmatching, when applied wherever possible, does greatly increase the amount of crossmatching work in the blood bank. The policy results in about a 70 percent increase in the workload for Rh positive crossmatches and about a 50 percent increase in the workload for Rh negative crossmatches. Because of the preponderance of Rh positive requests there is an overall increase of about two-thirds. Operation of the simulation model, using standard crossmatching, required about 12,000 Rh positive and about 1,300 Rh negative crossmatches during the simulated six-month period. Use of double-crossmatching added about 9,200 crossmatches to this total, 8,500 for Rh positive and 650 for Rh negative units.

Since this increase in workload seemed high, other policies were tried which restricted the use of double-crossmatching to those cases where the "old" unit of the pair of units satisfied some additional condition, such as older than x days or being one

blood leaving the blood bank (transfusions and expirations) are compared, there is almost no difference. Average age is then percent waste times age at expiration plus percent transfused times age at transfusion. The increase in age at transfusion is offset by the decrease in percent waste to achieve the parity of results.

of the oldest x percent of its blood type. The application of these restrictions had different effects on the wastage of Rh positive and Rh negative blood which will be discussed separately. The following two graphs show the relationship between wastage and workload increase in Rh positive blood for different levels of the previously stated restrictions:

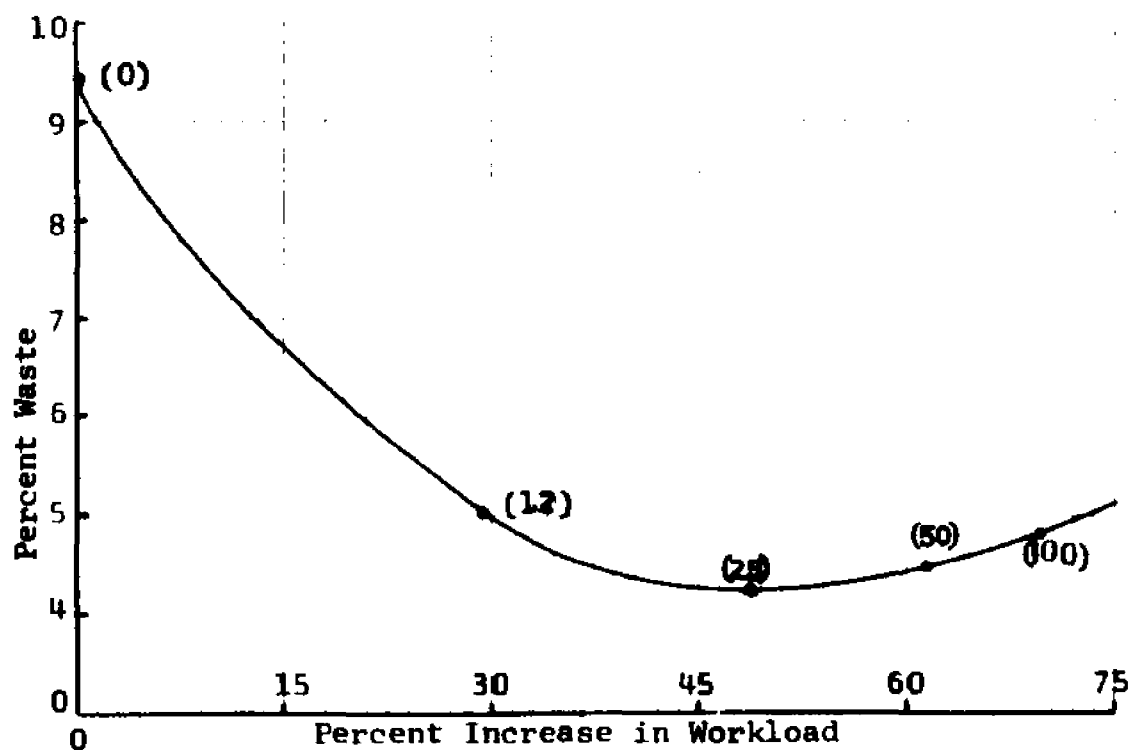


Fig. 12.--Relationship between wastage of Rh positive blood and percent increase in workload when the "old" unit is restricted to x days old or older. (Number in parentheses is the value of x)

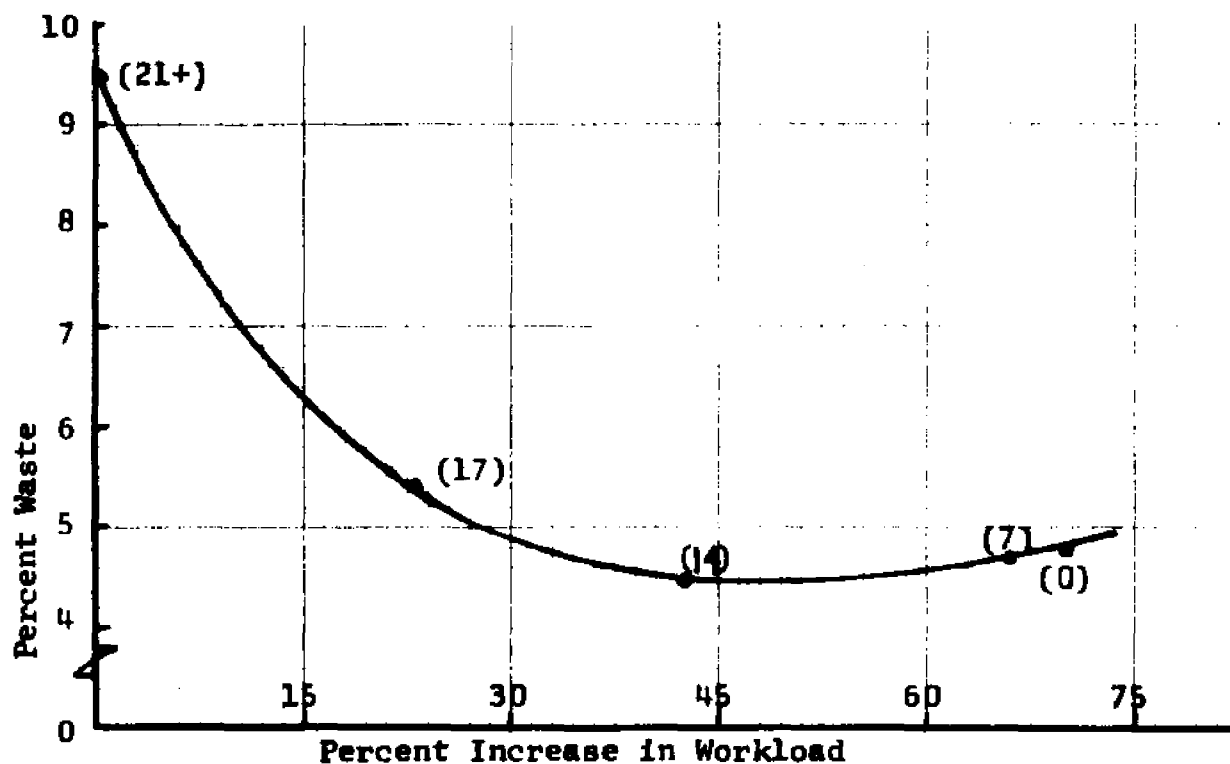


Fig. 13.--Relationship between wastage of Rh positive blood and percent increase in workload when the "old" unit is restricted to oldest x percent of its blood type. (Number in parentheses is the value of x)

Both graphs illustrate a very striking outcome: permitting double-crossmatching to be performed whenever possible does not lead to the greatest reduction in waste of Rh positive blood. Indiscriminate application of this policy probably led to some pairings (old with old, or new with new) which were not useful for reducing wastage. The additional restriction has limited the application of the double-crossmatching to only efficient pairings. Double-crossmatching reduced wastage of Rh positive blood from 9.8 percent to 4.4 percent when restricting the "old" unit to be 14 days of age or older, which is a reduction of about 55 percent,

while only incurring an increase of about 43 percent in the number of Rh positive crossmatches. Alternatively, the wastage was reduced from 9.8 percent to 4.2 percent when restricting the "old" unit to one of the oldest 25 percent of the units of its blood type. This reduction of more than 55 percent was achieved while incurring an increase of about 50 percent in the number of Rh positive crossmatches. These findings are summarized in the following table:

TABLE 29
EFFECT OF RESTRICTIONS ON WASTAGE AND
WORKLOAD FOR Rh POSITIVE BLOOD

Restriction on Double-Crossmatching	Reduction in Percent Waste	Increase in Workload
Unrestricted	50%	70%
"Old" unit 14 days old or older	55	43
"Old" unit one of the oldest 25 percent	57	50

Since these restrictions simultaneously achieve the dual result of further reducing the percent wastage and cutting down the extra crossmatching work, they (one or the other) can be unequivocally recommended for use in conjunction with the application of the double-crossmatching policy. The choice of the restriction to use would probably depend on its ease of implementation in the particular blood bank.

When the restrictions on double-crossmatching were applied to Rh negative blood, the effect was quite different. Double-

crossmatching, when applied to Rh negative blood, does not result in the large savings effected in Rh positive blood, since its application is limited by the relative infrequency of patients. Additional restrictions, like those discussed here, further limit its applicability and reduce even those savings that were obtained from unrestricted application of double-crossmatching. The following two graphs show the effect of these restrictions on wastage and workload increase associated with Rh negative blood:

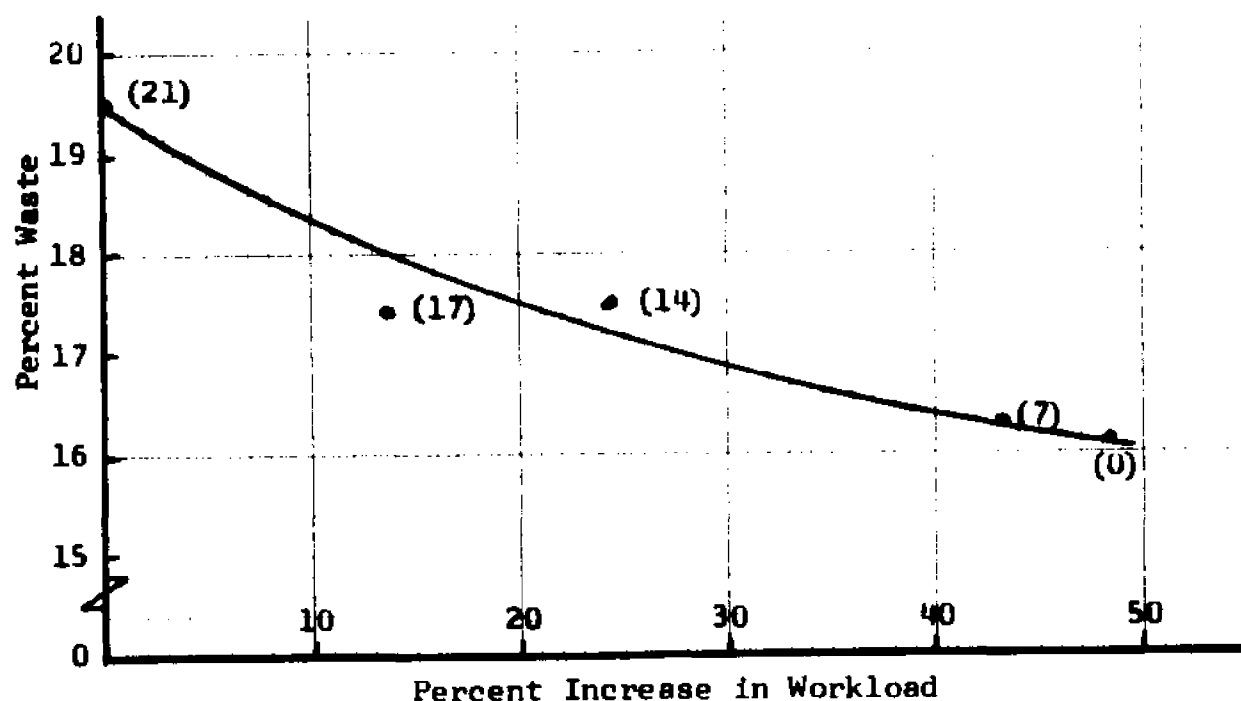


Fig. 14.--Relationship between wastage of Rh negative blood and percent increase in workload when the "old" unit is restricted to x days or older. (Number in parentheses is the value of x)

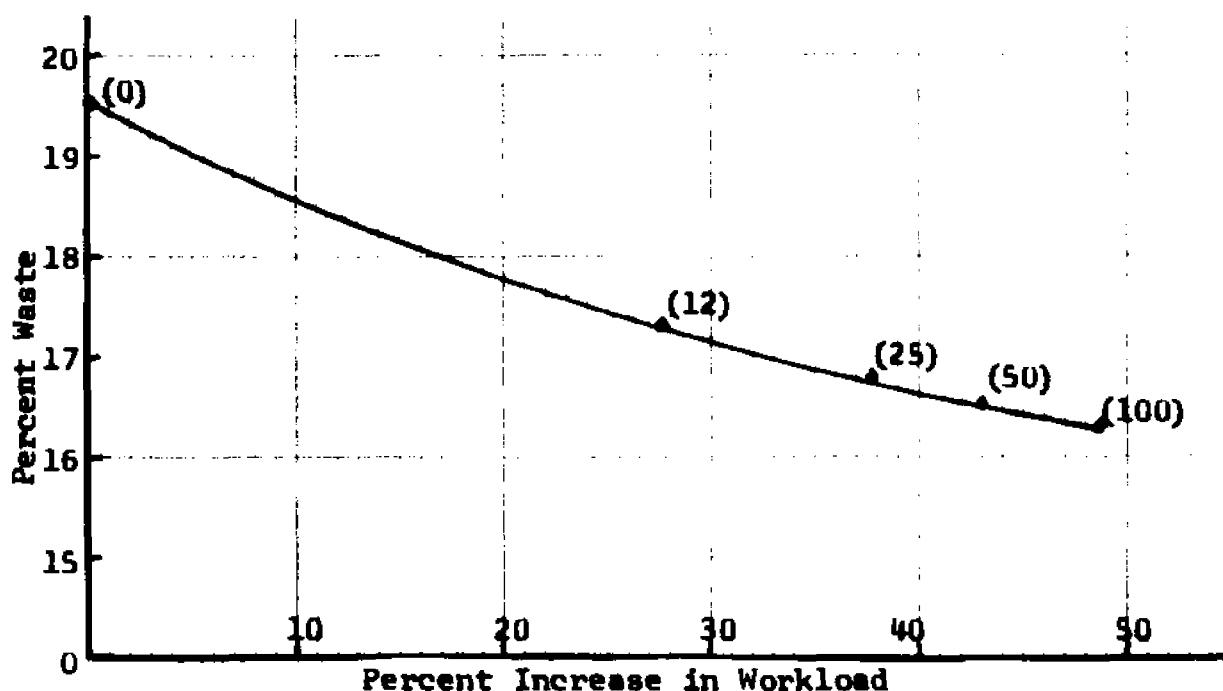


Fig. 15.--Relationship between wastage of Rh negative blood and percent increase in workload when the "old" unit is restricted to the oldest x percent of its blood type. (Number in parentheses is the value of x)

The effects of applying the same restrictions to Rh negative blood are distinctly different from those observed for Rh positive blood. Any restriction on the double-crossmatching of Rh negative blood serves to reduce the savings from that achieved when no restrictions were applied. Since double-crossmatching alone only resulted in a 20 percent reduction in waste, when used wherever possible, it would not be desirable to restrict its applicability, which would lower even the 20 percent gain. Moreover, the crossmatching workload associated with Rh negative requests is less than one-sixth of the total workload; even when

applied without restriction, double-crossmatching increased this work by only about 50 percent because of the limited availability of two patients.

The value of double-crossmatching, even with one of the above restrictions, depends on the utility of the wastage reduction compared with the disutility of the increase in work. While cost might be a reasonable measure of the disutility of work, the utility of a unit of blood is very difficult to measure because of its use in the saving of human lives. If cost is used as a measure of the utility of a unit of blood, this measure would certainly understate its true value. If the comparison of the cost reduction through the reduction of blood wastage to the cost increase due to increased work still shows double-crossmatching to be valuable, then it is certainly to be preferred.

Using the cost of a unit of blood and the cost of an additional crossmatch (approximately \$25.00 and \$0.25 respectively), the optimal policy is the one which minimizes the total cost, or maximizes the difference between the cost of saved blood and the cost of increased work.

When considering the total cost of various restrictions on the age of old blood, including no double-crossmatching and unrestricted double-crossmatching as the extreme choices, the minimum cost for Rh positive blood occurred at the 14-day point. When considering the total cost of various restrictions on the percentage of "old" blood, again including no double-crossmatching and unrestricted double-crossmatching as the two extremes, the

minimum cost for Rh positive blood occurred at the 25 percent point.

Since cost, which represents an understatement of the utility of a unit of blood was used in the calculations, it might be possible that less restriction would be desirable. But less restriction actually reduces the saving of blood, so that it can be concluded that double-crossmatching of Rh positive blood using one of the two recommended restrictions provides an actual improvement in the operation of a hospital blood bank.

When the same utility analysis performed for Rh positive blood was carried out for Rh negative blood, the results indicated that the minimum would be achieved if double-crossmatching was applied without any restrictions, that is, whenever two patient's requests were available for the same blood type;

It is therefore recommended that double-crossmatching be used for Rh positive requests when the older unit is 14 days old or older or is one of the oldest 25 percent of its blood type and that double-crossmatching be applied to Rh negative requests whenever possible. Table 30 shows the effect on wastage and workload of the recommended policies compared to current practice.

Use of "Old" Rh Negative Blood for
Patients Having Rh Positive
Blood and the Supply of
Rh Negative Blood

Allowing "old" Rh negative units to be used for patients having Rh positive blood results in a reduction in the wastage of Rh negative blood, with no increase in the waste of Rh positive blood. This does not involve any real increase in work. From

TABLE 30
EFFECT OF RECOMMENDED POLICIES ON
WASTAGE AND WORKLOAD

Blood Group	Single Cross-match All Requests	Double-Crossmatch Rh Positive Older than 14 days and All Rh Negative	Double-Crossmatch Rh Positive if in Oldest 25 pct. and All Rh Negative
Wastage (no. of units in a six-month period)			
Rh Positive Savings	445 ---	191 57%	179 60%
Rh Negative Savings	98 ---	78 20%	78 20%
Total Savings	543 ---	269 50%	257 53%
Workload (no. of crossmatches in a six-month period)			
Rh Positive Increase	12300 ---	17500 43%	18300 50%
Rh Negative Increase	1300 ---	1950 50%	1950 50%
Total Increase	13600 ---	19450 44%	20250 50%

the hospital blood bank's point of view, this policy provides improvement without any disadvantages. However, if a unit of "old" Rh negative blood is transfused to an Rh positive patient and then an Rh negative patient requests a unit, which he would have used before that unit's expiration, an additional unit of Rh negative blood would be needed and used by the blood bank. Thus, the policy introduces the possibility of the hospital's blood bank requiring excess units of Rh negative blood from its central sources, depleting the community's supply of the rarer Rh negative blood.

The evaluation of this policy must be made by balancing the utility of avoiding wasted units of Rh negative blood by using them for Rh positive patients against the disutility associated with drawing extra units of Rh negative blood from the community's supply. The utility of using Rh negative blood for Rh positive patients is obviously less than using it for Rh negative patients but greater than wasting the unit or extracting its plasma. As these utilities are very difficult to evaluate, the effect on wastage and the extra units required by allowing different age of Rh negative blood to be used for Rh positive patients are shown in the tables below. Since the use of double-crossmatching improves the effectiveness of this policy (as previously discussed), the effects are shown first for the blood bank using standard crossmatching and then for the blood bank using double-crossmatching.

While it is not intended to specify the relative utilities of reducing waste of Rh negative blood by using "old" units for Rh positive patients and the requiring extra units of Rh negative blood from the community's supply, some comments about the results in Table 31 can still be made. First, if double-crossmatching is implemented in the blood bank, this policy will reduce wastage of Rh negative blood from 19.5 percent to 16.2 percent and simultaneously reduce the blood bank's requirements of Rh negative blood (because less units were wasted) from 502 to 483 units for a six-month period. Then, if Rh negative blood 18 days or older is allowed to be used for Rh positive patients,

TABLE 31
EFFECT OF USING "OLD" Rh NEGATIVE BLOOD
FOR Rh POSITIVE PATIENTS

(six months simulated time)						
Age in Days at which Rh Negative Blood Becomes Available to Rh Positive Patients	No. of Transfu- sions to Rh Negative Patients	No. of Transfu- sions to Rh Positive Patients	No. of Units Wasted	Pct. Waste	Total No. of Units Req'd.	Extra Units Req'd.
Using Standard Crossmatching						
16	404	61	62	11.8	527	25
18	404	34	78	15.1	516	14
20	404	12	87	17.3	503	1
Not avail.	404	0	98	19.5	502	0
Using Double-Crossmatching						
16	405	83	30	5.8	518	35
18	405	65	33	6.6	503	20
20	405	24	57	11.7	486	3
Not avail.	405	0	78	16.2	483	0

the wastage will be further reduced to 6.6 percent while the number of units required will return to 503 units. Thus, the combined implementation of double-crossmatching and allowing Rh negative blood 18 or more days old to be used for Rh positive patients will result in a reduction in waste of Rh negative blood from 19.5 percent to 6.6 percent or 98 units to 33 units, while the number of units of Rh negative blood required at the blood bank can be maintained at the same level, 502 vs. 503 units. If the recommendation to use double-crossmatching is followed, it is further recommended that Rh negative units which are 18 days old or older be made available for Rh positive patients, since this policy will reduce wastage of Rh negative blood from the 16.2 percent level achieved with

double-crossmatching to 6.6 percent, while the number of units of Rh negative blood required will be maintained at about the same level as before both policies were implemented.

Recognition of "Special" Users and the
Problem of Blood Quality

The policy of identifying patients whose diagnoses imply that they are more likely to use the units of blood reserved for them and crossmatch these patients against the oldest units of their blood type has been shown to be very beneficial for a blood bank. It significantly reduces the wastage of blood of all types without causing any material increase in work required and may even result in a small reduction in the number of shortages. However, the application of this policy means that this class of patients will generally be transfused with blood which is almost 21 days old. This is not a problem for most patients since 21-day old blood is still acceptable in general. The classes of patients found to have a much higher probability of using reserved blood are anemia patients and out-patients (most of whom are also suffering from anemia but don't have to be hospitalized). Most of these, because of the nature of their illness, require blood which is fresher than 21 days of age. The problem occurs because the illness causes the breakdown of the red blood cells, which is what happens as blood ages in a blood bank. These patients' blood already contains waste material caused by the breakdown of the red blood cells, which the body has problems in removing from the blood stream. To transfuse these patients with blood which

also has large quantities of dead red cells would be unacceptable. Even though these "special" patients represent about 7-8 percent of all patients requesting blood, only about a quarter of them, or about 2 percent of all patients, are expected to be able to be transfused with old units of blood. This would greatly reduce the effectiveness of this policy, estimated on the assumption that about two-thirds of these patients, or about 5 percent of all patients, could be transfused with old units of blood.

However, recent advances in blood storage may enable these "special" users to be transfused with older units of blood. A new preservative, CPD, is presently being introduced into blood banking. This preservative will significantly improve the quality of all blood by maintaining a higher percentage of viable red cells for the entire life of the unit. It is expected that the viability of old blood using this new preservative will be equivalent to or higher than 14-day old blood stored with the previously used ACD preservative. In this case, the units would have enough good red cells to be acceptable for transfusion to anemia patients. The problem of impurities in the blood can also be solved by "washing" it. A unit of "washed" red cells is the equivalent of a unit of packed red cells from which other materials (including impurities) have been "washed" out. Washed red cells suffer from the restriction that they must be transfused within 24 hours after washing, or the unit will be wasted. This is not really a problem with old units since they would probably have been wasted in any case, if not transfused within a day or two. It is hoped that the availability

of the more effective preservative, together with the ability to "wash out" the impurities from old units of blood, will make the "special" user policy effective in reducing blood wastage by allowing more of these "special" patients to be transfused with older blood.

Effects of the Parameters Associated With the Use of Double-Crossmatching

The definition of "old" blood

Double-crossmatching's effectiveness arises from the fact that a unit of "old" blood and a unit of "young" blood are reserved against each patient's request. This means that each unit of "old" blood that is reserved will be available to two patients, as will the matching unit of "young" blood. If either patient requisitions a unit of blood, the "old" unit will be used, thus reducing the chances of that unit going out of date. In order for this policy to be implemented in the blood bank, there must be some definition of what constitutes an old unit of blood. This parameter of the double-crossmatch policy was arbitrarily set so that the oldest one-third of each blood type was considered "old" and the remaining units were considered "young" in all case studies using the double-crossmatching policy.

However, this definition may affect the operational effectiveness of the double-crossmatching policy, so a set of experimental cases was run using different definitions for "old" blood to investigate the effect of this variable on the percent waste

obtained when using double-crossmatching. The following table shows the results of these cases:

TABLE 32
EFFECT OF VARYING THE DEFINITION OF "OLD" BLOOD
ON WASTE WHEN USING DOUBLE-CROSSMATCHING

Definition of "Old" Blood	Pct. Waste Rh Positive	Pct. Waste Rh Negative	Pct. Waste Overall
Oldest 50% of each Type	4.9	17.4	6.2
Oldest 33% of each Type	4.8	16.2	5.9
Oldest 25% of each Type	5.1	16.6	6.2
Oldest 20% of each Type	5.5	16.7	6.6

These results show that the definition of "old" blood does effect the wastage that occurs when using double-crossmatching. However, the variation in wastage is relatively small for the definitions between the oldest 25 percent and the oldest 50 percent, indicating that the policy is not overly sensitive to the setting of this parameter. It does seem to be most effective when using the one-third oldest definition. In addition, several cases varying the definition of "old" blood were also run using the 14 day old or older restriction on the applicability of double-crossmatching and these cases also showed very little variation in results. The overall difference in percent waste was less than 0.1 percent when varying the definition between the oldest 33 percent to the oldest 50 percent.

The required proximity in time
(days) between the pair of re-
quests to be double-crossmatched

In order to double-crossmatch patients' requests, the blood bank must crossmatch two different patients against each unit being reserved. The question of how closely in time the two patients' requests must arrive at the blood bank is a factor that affects the number of possible double-crossmatches that can be performed, therefore affecting the workload as well as the effectiveness of double-crossmatching.

In the cases run to evaluate the effectiveness of double-crossmatching, the pairing was attempted whenever possible. Any time a unit of blood was on reserve, and another patient requested a unit of that type, the simulator attempted to pair these patients to form a double-crossmatch. This strategy results in maximum work and also in maximum effectiveness of double-crossmatching. If, however, it is not desired to search through the reserved units to find double-crossmatches or if this searching provides operational problems in a hospital blood bank, it may only be possible to double-crossmatch two patients whose requests arrive at the blood bank on the same day. A set of cases was run on the simulator to evaluate the effect of this "same day" requirement on the operation of the double-crossmatching policy. The results of these cases are shown in the following table:

TABLE 33

EFFECT OF "SAME DAY" REQUIREMENT ON WASTAGE AND
WORKLOAD WHEN USING DOUBLE-CROSSMATCHING

Policy	Percent Wastage			Pct. Inc. in Work ^a		
	All Units	Rh Pos.	Rh Neg.	All Units	Rh Pos.	Rh Neg.
Double-Crossmatching (no restrictions)						
Same Day Not Req'd.	5.9	4.8	16.2	68	70	50
Same Day Required	6.5	5.2	17.2	45	47	31
Double-Crossmatching ("old" unit 14 days old or older)						
Same Day Not Req'd.	5.8	4.4	17.6	41	43	26
Same Day Required	6.9	5.7	17.9	27	29	16

^aOver the workload that is required for single crossmatching.

These results indicate that the "same day" requirement reduces considerably the number of possible double-crossmatches and the associated workload from the level achieved when this requirement was not imposed. The percent wastage is also increased over that achieved by double-crossmatching without the "same day" restriction, because the ability to form double-crossmatches has been reduced. The specific effect is to reduce the workload about one-third, from 68 percent to 45 percent more than standard crossmatching when not using the 14-day restriction and from 41 percent to 27 percent more than standard crossmatching when using the 14-day restriction. The percent wastage only increased by about one-sixth, from 5.9 percent to 6.5 percent and from 5.8 percent to 6.9 percent without and with the 14-day restriction respectively. Thus, the "same day" requirement investigated because of practical

operational considerations, seems to provide a beneficial trade-off between workload and wastage. This can only really be evaluated by comparing the utility of not wasting units of blood with the disutility of increased workload.

Summary of Findings

Effect of various policies on shortages

Previous researchers have reported on the relationship between desired inventory level and wastage and shortages occurring in a blood bank. The simulator also verified these findings, which are standard in any inventory situation, in that as desired inventory level is raised, shortages decrease and wastage increases. As desired inventory level is lowered, shortages increase and wastage decreases. The desired inventory levels used in the simulator reflect those in actual use at the Mount Sinai Hospital Blood Bank. The resultant wastage levels were very close to actual wastage of 11 percent incurred at Mount Sinai Hospital over the last two years for which data are available, 1967-1968.

When the three policy variations were tried, using the simulator, the shortages incurred varied very little from those observed when using the standard crossmatching policy. Thus, it can be concluded that the inventory level may be set to establish an "acceptable" number of shortages over a period of time. These policy changes can then be used to reduce the wastage levels.

Double-crossmatching

The effect of the double-crossmatching policy on wastage

of the more predominant blood types, the Rh positive types in general, and A+ and O+ in particular, was to reduce the wastage considerably. The effect on the rarer blood types, however, was not as marked, since for double-crossmatching to be effective, there must be two patients requesting blood at the same time, which does not happen as often with the rarer blood types as with more prevalent types. On an overall basis, the double-crossmatching policy effected a reduction of waste of about 50 percent from the levels achieved under present policies.

However, the use of the double-crossmatching policy, when applied without restriction, greatly increases the amount of crossmatching work that has to be performed at the blood bank. The policy results in a 70 percent increase in the workload on Rh positive blood types and a 50 percent increase in the workload on Rh negative blood types, an overall increase of approximately two-thirds.

Since this was a considerable increase in workload, several policies were tried which restricted the use of double-crossmatching to those cases where the "old" unit satisfied some additional condition, such as older than x days or one of the oldest x percent. Some of these policies, which limited the application of double-crossmatching, were very successful. In particular, the policies which limited double-crossmatching of Rh positive blood to those cases where the "old" unit was 14-days old or older, or among the oldest 25 percent of its blood type, resulted in a reduction in waste even greater than that achieved

when the policy was used for all units. This result was probably achieved by forcing greater concentration of effort among the older units. In addition, the increase in the Rh positive workload, when applying either of these limitations, was between 40 and 50 percent. Thus, reduction in workload from that of unrestricted double-crossmatching was achieved while obtaining greater benefits than those of unrestricted double-crossmatching.

Because of the limited number of patients, a savings of 20 percent was the maximum available through double-crossmatching of Rh negative blood. For the same reason, the increase in Rh negative work caused by double-crossmatching was only 50 percent. Any restrictions on double-crossmatching of Rh negative blood reduced the savings from that achieved when no restrictions were applied. Since the increase in Rh negative workload is only a small fraction of the total workload, reducing it has a negligible effect and it was considered more desirable not to reduce the 20 percent savings.

"Old" Rh negative blood used
for Rh positive patients

Since the demand for Rh negative blood is much less than that for Rh positive blood, the wastage levels for these "rare" blood types are much higher, approximately double the predominant blood types. One reason these units are wasted is that there are times when there are few or no Rh negative patients requesting blood. In these cases, Rh negative blood merely ages in inventory and goes out of date. However, if the "old" Rh negative blood units were made available to Rh positive patients, some of this

wastage could be prevented. On the other hand, the usage of the Rh negative blood results in increased demand on outside sources if Rh negative patients become available after the blood was given to an Rh positive patient but before its expiration date. If no Rh negative patient had requested the unit during this interval, the unit would have been wasted and been replaced to bring the inventory back to its desired level. When units 20 days old or older are made available, there is a small decrease in the wastage (approximately 10 percent) but only a negligible increase in the demand the hospital blood bank places on the central sources. When units 18-days old or older are made available, there is a larger decrease in the wastage (approximately 20 percent) accompanied by a small but noticeable increase in orders placed at the central sources. Continued lowering of the age at which Rh negative blood is made available to Rh positive patients would result in an excessive drain on the community's supply of "rare" blood.

Recognition of "special" users

Among all users of blood in a hospital, only about 50 percent of all units ordered and reserved for a patient are ever requisitioned. Even some of these units are returned. Since each reservation consumes approximately 2 to 3 days of a unit's life, this demand behavior contributes greatly to wastage. When a unit that is over 18 days old is crossmatched against a request from a patient who does not use it, there may not be sufficient time for the unit to be crossmatched against another patient's request before it expires.

If, when a unit became old, there was some way to reserve it for a patient who was more likely to use it than the average patient, then the wastage rate could be reduced greatly. Analysis of usage by patient type indicated that two types of patients, out-patients and anemia patients, use proportionately a greater percentage of the units they reserved. If it were possible to transfuse old units to these patients, the wastage rate could be significantly reduced. These represent between 7-8 percent of all patients and if two-thirds of them can be classified as able to receive "old" blood and if every effort is made by the blood bank to reserve old blood against these patients' requests, then the wastage of blood can be cut by about 30 percent, mainly among the more prevalent blood types. If this concept is used in combination with the policy of making "old" Rh negative units available to Rh positive patients, a significant improvement in the wastage of rare blood is also possible.

APPENDICES

APPENDIX I

EXISTING HOSPITAL RECORDS AND DATA COLLECTION

Receipt of BloodHospital records

Each unit of blood¹ which arrives at the hospital blood bank is recorded in the "Donor Book". The following information is recorded for each unit of blood:

1. Donor Number (a five digit sequential number assigned to each unit received at the blood bank.)

Bought Blood

- 2a. Source
- 3a. Blood type
- 4a. Date drawn

Donated Blood

- 2b. Donor's name and address
- 3b. Name and relation of patient for whom donation is made
- 4b. Date drawn which is the same as date received

Data collection

For each unit of blood received during the data collection period, the following information was taken from the hospital records:

1. Donor number
2. Source - coded identification for each bank and for 3 classes of donors (W.B.B., polycythemia, other donors, e.g. friends, relatives)

¹A unit of blood in this study is considered to be a unit of whole blood (500 ml.) or a unit of packed cells, i.e. whole blood less some plasma resulting in a unit of approximately 250-300 ml. which is considered equivalent.

3. Blood type (for donated blood the blood type is not recorded and this information is obtained from the blood unit's identification tag)
4. Date drawn
5. Date received (same as date drawn for donated blood) was inferred for bought blood in the following manner:
 - a) Estimated on the basis of surrounding dates on donated blood.
 - b) Counts of blood by date were then checked against hospital counts of blood received from each bank on that date to verify any dates still not completely certain.

The above data were put in computer usable form by key-punching them into IBM cards in the following format:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1	5	Code for donor book data
2 - 7	Date received	e.g. April 15, 1968 = 041568
8 - 13	Date drawn	(see above)
14 - 15	Source of blood	See Table A1-2 for code
16 - 20	Donor number	
21	Blood type	See Table A1-1 for code

Information on approximately 5000 units of blood received between March 1, and June 30, 1968, were collected for analysis.

Usage of Blood

Request for Crossmatch and Reservation

Hospital records

A request for a unit of blood is originated by a patient's physician who fills out a 3-part request form for each unit of blood to be put aside for that patient. The following information is

entered on the form at the originating point:

1. Date
2. Patient's name, ID, location, sex, age
3. Physician or service
4. Tentative diagnosis
5. Request - i.e., typing or for reservation; whole blood or packed cells, or washed blood, etc.

This request is forwarded to the blood bank together with a pilot tube of the patient's blood (unless one is already at the blood bank). The request is stamped with the date and time of its arrival at the blood bank when it is received. The pilot tube is typed first if that has not already been done.

The request is then sent for crossmatching. When the crossmatching has been completed by the technician, the following information is inserted into the report section of the request:

1. Patient's blood type
2. Donor's blood type
3. Donor number
4. Results of the three compatibility tests (Saline, Enzyme and Coombs - all results should be negative)
5. Date of crossmatch
6. Blood bank number, which is the number assigned to the crossmatch in the "compatibility book". This number becomes the reference to the record of the crossmatching contained therein.
7. The technician also stamps the following day's date on the slip to insure that the unit of blood just crossmatched will remain on reserve for the specific patient for at least 24 hours.
8. A strip of tape with patient identification blood type, location and donor number is attached to the tag of the compatible unit.

9. The patient's chart copy of the request is clipped to the tag of the crossmatched unit of blood and these, together with a patient card, are placed on the reserve board.

Data collection

For each request for crossmatching received during the data collection period, the following information was taken from the laboratory copy (part 2 of the 3-copy form):

1. Patient's ID number
2. Code for emergency, if indicated on the request slip
3. Pay category of the patient, e.g. PVT. S.P., or Ward. This was determined by the presence or absence of a private physician.
4. Patient's age
5. Patient type (e.g., Leukemia, Open Heart, etc.) was determined from tentative diagnosis.
6. Patient's blood type
7. Donor blood type
8. Donor number
9. Date and time request arrived at blood bank
10. Date of crossmatch

The above data were put in computer usable form by being keypunched into IBM cards in the following format:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1	1	Code for request for crossmatch data
2-7	Patient ID	Patient unit number
8	Emergency code	0 = non-emergency 1 = emergency
9	Pay category	1 = semi-pvt or pvt 2 = ward
10	Patient's age	See Table A1-4 for code
11	Patient type	See Table A1-3 for code
12	Patient blood type	See Table A1-1 for code
13	Donor blood type	See Table A1-1 for code
14-18	Donor number	
19-24	Date of arrival of request	
25-28	Time of arrival of request	
29-34	Date of crossmatch	

Information on approximately 12,000 requests for crossmatch and reserve made between March 1, and June 30, 1968, were collected for analysis.

Cancellation of Reservation (Request Taken-off Reserve)

Hospital records

A request for crossmatching causes a unit of blood to be put on reserve for a patient. If, after this unit has been reserved, no requisition of the reserved unit is made within a specified period, then the unit is reclassified back into the regular inventory, the original request is cancelled and the request slip is separated from the unit of blood. This check for unrequisitioned reserved blood is made at 8:00 A.M. each day. If a request is cancelled, the patient's chart copy of the request slip (copy 1 of the

3-copy request) is detached from the tag representing the reserved unit of blood and the strip of tape with the patient identification, etc. is removed from the blood tag and placed on the patient's chart copy of the cancelled request. These cancelled requests are normally held for 24 hours and then discarded.

Data collection

Upon request, the cancelled reservation request slips were not discarded so that the following data could be obtained from them:

1. Patient identification
2. Donor number
3. Date request taken off reserve. This is not recorded on the slips, but they were obtained each morning so that the date taken off reserve could be assigned.

This information was put in computer usable form by having it keypunched into IBM cards in the following format:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1	2	Code for taken-off reserve
2-7	Patient ID	
8	Blank	
9-13	Donor number	
14-19	Date taken-off reserve	

The data collected for analysis included approximately 5000 cancellations of reservations which occurred between March 1, and June 30, 1968.

Requisition of Reserved Blood (Call for Slip)

Hospital records

When the reserved units of blood are needed, the physician fills out a requisition slip called a "Request for Blood Components". The physician fills in the date, patient identification and location, physician or service and indicates how many units (up to a maximum of 3 per form) of which blood components he needs. This slip is sent to the blood bank where the units which have been reserved for that patient are found. Starting with the oldest unit, the number of units requested, which may be less than the number on reserve for that patient, are sent out. The donor numbers for the units sent out are entered upon the call-for slip together with the patient blood type and type of component.²

The tag representing the unit of blood is divided into two parts. The top half together with the patient's chart copy of the request for crossmatch are attached to the unit of blood being disbursed. The bottom half of the tag from that unit of blood is stapled to the call-for slip which remains in the blood bank.

Data collection

For each requisition of reserved blood received during the data collection period, the following information was taken from the requisition slip:

²If the requisition originates in the operating room area then the blood bank fills in the blood unit numbers upon a telephone request and sends up the partially completed call-for slip with the unit of blood to the operating room where the slip is completed with patient identification, etc., and brought back to the blood bank by the person who delivered the units of blood.

1. Patient identification
2. Donor number(s) called for
3. Date the units of blood were called for or delivered to the requisitioning physician

This information was put into computer usable form by being key-punched into IBM cards in the following format:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1	3	Code for a call for slip
2-7	Patient ID	
8-9	Blank	
10	Number of units requested	
11-16	Date blood was "called for"	
17-21	First donor number	
22-26	Second donor number (if any)	
27-31	Third donor number (if any)	

The data collected for analysis included approximately 5000 requisitions of reserved blood which occurred between March 1, and June 30, 1968.

Return of Requisitioned Blood

Hospital records

If a unit of blood requisitioned by a physician is not transfused into the patient, that unit may be returned to the blood bank, provided it has been stored properly, i.e., refrigerated for the time that it was out of the blood bank. The return of blood to the hospital blood bank is recorded in one of two ways.

If the return is made soon after the unit was sent out so that the call for slip had not been sent out to the accounting department for billing purposes, then the word "return" and the date returned are entered on the half of the tag representing that unit of blood, stapled to the call for slip. In addition, the donor number written on the call for slip is crossed out.

If the return is made after the call for slip had been sent out for billing, then the top half of the tag and the patient's chart copy of the request for crossmatch slip are detached from the returned unit. The word "return" together with the date returned are written across the top half of the tag so that it can be sent to the accounting department to correct the previous charge.

Data collection

For each return of untransfused blood made during the data collection period, the following information was taken, either from the bottom half of the blood unit's tag and call for slip, if it was recorded there, or from the top half of the blood unit's tag and the request for crossmatch copy, if it was recorded there:

1. Patient identification
2. Donor number(s) returned
3. Date the unit(s) of blood were returned

This information was put into computer usable form by being key-punched into IBM cards in the following format:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1	4	Code for a return
2-7	Patient ID	
8-9	Blank	
10	Number of units returned	
11-16	Date blood was returned	
17-21	First donor number	
22-26	Second donor number (if any)	
26-31	Third donor number (if any)	

The data collected for analysis included approximately 1000 returns of called for blood which occurred between March 1, and June 30, 1968.

TABLE A1-1
BLOOD TYPE CODES

Blood Type	Code
A+	1
A-	2
B+	3
B-	4
AB+	5
AB-	6
O+	7
O-	8

TABLE A1-2
SOURCES OF BLOOD

Source	Code
Walking Blood Bank	1
Polycythemia Donor	2
Donor	3
Red Cross	4
New York Blood Center	5
Pioneer Blood Bank	6
National Blood Bank	7
Elmhurst Hospital	8
Inter-County Blood Bank	9
Pfizer Diagnostics	10
Greater New York Blood Program	11
Empire Blood Bank	12
Other	13

TABLE A1-3
PATIENT TYPES

Patient Type	Code
Anemia	1
Bleeder	2
Exchange	3
Hemophilia	4
Leukemia	5
Maternity	6
Open Heart	7
Operating Room	8
Out Patient	9
Others	0

TABLE A1-4
PATIENT AGE

Age	Code
No age	0
New Born	1
Under 1 Year	2
1-5 Years	3
6-12	4
13-18	5
19-35	6
36-50	7
51-65	8
Over 65	9

APPENDIX II

DATA ORGANIZATION AND VERIFICATION

Introduction

Because of the large number of data records which were collected, (approximately 25,000, each consisting of several pieces of information) there was a very high probability that many errors might have been made in the data collection. These errors could be of small or large magnitude and could have occurred at any step in the record keeping-data collection process. Errors of the following types might occur:

1. Original errors, i.e., errors in recording on the hospital's forms. These could be date errors, donor number errors, patient identification errors, etc., or they could be errors of omission, i.e., one or more pieces of information could be missing from the hospital records.
2. Coding errors. Information such as source of blood, patient age, blood type, patient type, etc., coded before being transcribed could incur errors in the coding, itself.
3. Missing records. Since the hospital records were obtained from the blood bank after the blood bank was finished with them (this being from a day to a couple of months after they were recorded), there is always a possibility that some of the forms could be lost or misplaced after serving their purpose at the blood bank.

4. Transcription error. These are the errors made in the transferring of the information from hospital forms to coding forms for keypunching into IBM cards.
5. Keypunching errors. Errors made by the keypunch operators in punching the information from coding forms into IBM cards, to put information into machine readable form.

As the presence of too many errors in the data would distort any statistical analysis that was performed, it was deemed necessary to check the data as well as possible to correct as many errors as feasible. The data checking technique employed was that of logical internal consistency within the data rather than the completely impractical method of proof-reading against the original forms (which would not have helped in errors of types 1 or 3).

Data Organization

In order to accomplish this logical data check, the data had to be organized in a special format. This format put all the data associated with a particular unit of blood together; within the total set of data for a unit, the data were organized into subsets called "transactions".

A transaction represents a single set of events that would cause the inventory status of a unit of blood to go from regular inventory to "reserved" and then either back to regular inventory or to actual use in a transfusion. If we relate to the hospital records and to the information collected from them, there are only three possible sequences of events, i.e. three possible sets of

records that would constitute a valid transaction. These are as follows:

1. a) Request for Reservation (crossmatch slip)
b) Cancellation of Reservation (taken off reserve)
2. a) Request for Reservation (crossmatch slip)
b) Requisition of Reserved Blood (call for slip)
c) Return of Requisitioned Blood (return slip)
3. a) Request for Reservation (crossmatch slip)
b) Requisition of Reserved Blood (call for slip)

The first two transaction types result in the unit of blood being re-available to the blood bank for use by some other patient, but the third transaction type must be the last transaction for that unit of blood. If the unit were never transfused, the last transaction type for that unit would be either Type 1 or Type 2.

Having defined what is meant by a transaction, it is possible to explain how the data were arranged to achieve an ordering by units and by transactions within units. The following procedure was used:

1. Each of the five data sets was recorded onto magnetic tape from the original punched cards. The five data sets are as follows:

<u>Data Set No.</u>	<u>Information</u>
1	Request for Reservation
2	Cancellation of Reservation
3	Requisition of Reserved Blood
4	Return of Requisitioned Blood
5	Receipt of Blood

2. Each of the five data sets was sorted into sequential order, with the major sort field being the donor number

(i.e. the blood unit's number) and the minor sort field (if necessary) being the data of the particular event (e.g., date crossmatched, date received, date returned, etc.) if there was more than one event of a particular type for a unit of blood.

3. A computer program was written that took the ordered records in each of the five input data files and merged them together in such a way as to create, where possible, complete transaction sets within each donor number. These merged records were put on magnetic tape to be checked for errors.

A sample section of the merged tape is shown below:

SAMPLE OF MERGED DATA

```

5 40268 32568 4490637999999
127492102817749063 403681554 40368
3274921 2 4046849063
4274921 1 4046849063
133936701767749063 405681540 40568
2339367 49063 40668
126630902687749063 407681018 40768
2266309 49063 40868
171164702787749063 409681001 40968
3711647 1 4106849063

```

This listing shows all the events that affected the inventory status of one unit of blood, donor number 49063. The first record represents the receipt of the blood at the blood bank. It contains the following information:

1. Blood drawn on 3/25/68
2. Blood received on 4/02/68
3. Received from the Red Cross (coded as 4)
4. Donor number 49063
5. Blood type O+ (coded as 7)

Each set of events for a unit of blood must begin with a Type 5 data set to indicate the receipt of the blood at the blood bank.

The second record is a request for crossmatch and reservation and contains the following information:

1. The identification number of the patient for whom the request was made is 274921.
2. This is not an emergency request (coded as 0).
3. The patient is a ward patient (coded as 2).
4. The patient's age is between 51-65 years (coded as 8).
5. The patient's diagnosis is anemia (coded as 1).
6. The patient's and the donor's blood types are both O+ (coded as 77).
7. The patient was crossmatched successfully with donor number 49063.
8. The request was received at the blood bank at 15:54 (i.e. 3:54 P.M.) on 4/03/68.
9. The crossmatch (and reservation) was performed on 4/03/68.

The third record is a requisition for the unit of blood on reserve. It contains the following information:

1. Identification number of the patient for whom the unit is reserved = 274921.
2. The number of units requested = 2.
3. The date the units were sent for = 4/04/68.
4. The donor number of this unit = 49063.

The fourth record is a return of the unit of blood previously requisitioned. It contains the following information:

1. Patient identification number = 274921.
2. The number of units returned = 1.
3. The date the unit was returned = 4/04/68.
4. The donor number of the returned unit = 49063.

It can be seen that the 2nd, 3rd and 4th records for unit number 49063 form a complete transaction of the second type. Similarly, records 5 and 6 as well as records 7 and 8 each form a complete transaction of the first type. And the last two records form a transaction of the third type indicating the final disposition of this unit of blood as being transfused to patient number 711647 on April 10, 1968. It was transfused to the fourth patient for whom it had been crossmatched, eight days (out of a maximum life of twenty-one days) after it had been drawn from the donor.

Data Verification

Once the data were organized, as described in the previous section, it was possible to make a thorough, logical check of the data so that they are internally consistent. The following is a list of logical consistencies that were insisted upon within a set of data for a particular unit of blood; violation of any one of

these principles would signal that an error existed in one or more of the records associated with that unit:

Logical Criteria Used in Checking Data

1. There must be a record of the receipt of the unit of blood in the blood bank.
2. The date drawn must be on or before the date the blood was received.
3. The date the unit was first crossmatched must be on or after the date it was received.
4. The unit's type, as recorded when received, must be the same as when it was crossmatched.
5. The date the crossmatch was requested must be on or before the day the crossmatch was performed.
6. If the reservation was cancelled,
 - a) the patient identification on the cancellation must agree with the patient identification on the crossmatch request;
 - b) cancellation of the reservation must be on or after the day the crossmatch was performed.
7. If the unit was called for,
 - a) the patient identification on the call for data must agree with the patient identification on the crossmatch request;
 - b) the date the call for slip was honored must be on or after the day the crossmatch was performed.
8. No transaction can have both a cancellation of reservation and a call for slip.
9. A return of blood was only permitted if there was a call for slip for that unit of blood, and in addition,
 - a) the date returned must be on or after the date called for;
 - b) the patient identification on the return must be the same as the patient identification on the call for slip.
10. No further use of a unit of blood is permitted unless the previous transaction ended in a cancellation or a return.
11. The crossmatch date on the second and succeeding transactions must be the same as or later than the latest date of the previous transaction.

12. If a crossmatch request has been made, there must be either a cancellation of the reservation or a call for slip for that patient; i.e., each set of data must form a complete transaction.

A computer program was written which subjected the merged data to the logical consistency checks just listed and if any violation was detected a message was printed out which indicated which unit of blood contained the error as well as some indication of the error that was detected. In addition, the complete set of data pertaining to that unit of blood was printed out so that the exact nature of the problem could be determined.

A sample section of the error listing is shown below.

SAMPLE ERROR LISTING

ERROR NO. 9 REUSE-NORTRN ERROR
 ERROR NO. 7 CD2 AND CD3 MISSING
 ERROR NO. 15 PAT. ID. CD3 ERROR
 ERROR NO. 16 DONOR NO. CD3 ERROR
 ERROR NO. 8 DATE CALLFOR ERROR
 ERROR NO. 9 REUSE-NORTRN ERROR
 ERROR NO. 13 PAT. ID. CD2 ERROR
 ERROR NO. 5 2+3OR4 PRSNT ERROR

DONOR BOOK DATA - DONOR NO.=52034, DATE DRAWN=60468, DATE RECVD=60568, SOURCE=

CROSS-MATCH DATA			TAKEN OFF RESERVE DATA			CALL FOR	
DATE	PATIENT NO	DONOR NO	DATE	PATIENT NO	DONOR NO	DATE	PATIENT NO
60668	417417	52034	-1	-1	-1	60668	417417
61668	291508	52034	-1	-1	-1	-1	-1
61868	713658	52034	61868	251508	52034	61868	713658

THIS SET OF DATA ENDS AT CARD NO. 23501

This listing shows all the logical criteria that were violated by errors in the three transactions performed with blood unit number 52034. The first error refers to the fact that the blood

has been made, there must be either a reservation or a call for slip for that of data must form a complete transaction.

as written which subjected the merged policy checks just listed and if any violation was printed out which indicated which error as well as some indication of

In addition, the complete set of data blood was printed out so that the exact error was determined.

The error listing is shown below.

SAMPLE ERROR LISTING

ERROR

MISSING

ERROR

ERROR

ERROR

ERROR

ERROR

ERROR

2034, DATE DRAWN=60468, DATE RECVD=60568, SOURCE=11, BLOOD TYPE=3

TAKEN OFF RESERVE DATA			CALL FOR DATA			RETURN DATA		
DATE	PATIENT NO	DONOR NO	DATE	PATIENT NO	DONOR NO	DATE	PATIENT NO	DONOR NO
-1	-1	-1	60668	417417	52034	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1
1868	251508	52034	61868	713658	52034	-1	-1	-1

NO. 23501

tical criteria that were violated

tions performed with blood unit

refers to the fact that the blood

was re-crossmatched on 6/16/68 after seemingly being transfused on 6/6/68. The message indicated that a return had to occur if the rest of the transactions happened. The second through sixth error messages pertain to the second transaction and all occurred because the program could not find a complete transaction. The cancellation of the reservation was not recognized because the patient identification number was in error and was included in the third transaction instead of the second. This false placement of the "taken off reserve" data also caused the last two error messages, which pertain to the third transaction. The incorrect patient identification is obvious, and the presence of both a reservation cancellation and call for data in the same transaction is not possible.

A search of hospital records indicated that the unit of blood which was called for on 6/6/68 was in fact returned on 6/11/68. The patient identification error in the taken off reserve data was also corrected by locating the original hospital form. The correction of these two pieces of data eliminated all the logical errors affecting blood unit number 52034 and the data were considered acceptable for statistical analysis.

Data Correction

Most of the errors that were reported by the error-detection program were relatively easy to correct. If a piece of data seemed to be in error, the original source document was located and the error was corrected from the data contained. If the error was not correctable in this manner, or if it was a result of missing data rather than erroneous data, secondary sources of information were consulted.

The name of the patient involved in the erroneous transaction was obtained by referring to one of the original documents for that transaction. The blood bank maintains a patient card file which contains a record of all units crossmatched for each patient, when (and if) they were called for, and when (and if) they were returned. By checking transaction information against the transactions recorded on the patient's card, it was possible to correct most of the remaining errors detected by the program.

The hospital blood bank also maintains a crossmatch book, in which the results of every crossmatching is recorded. Any errors resulting from discrepancies in crossmatching records (dates, patient identification, unit number, etc.) could be checked against the entry in the crossmatch book and corrected.

These procedures were carried out for each of the errors listed by the computer program until each error was corrected. The corrected transaction records were then considered valid and were used to obtain the necessary statistical data for the simulation.

APPENDIX III

STATISTICAL ANALYSIS OF THE DATA

Analysis of Blood Received at the Hospital

The error detection program provided a complete magnetic tape file of all transactions pertaining to each unit of blood, once all errors in the data were corrected. This transaction listing was in blood unit order and the transactions for a particular unit were in date order within the unit. A computer program was written to perform the following statistical breakdowns so that analysis could be performed to provide the input data for the simulator.

Analysis of source of blood

The first data set for each unit of blood contains the source of the unit of blood and the blood type, as well as the date drawn and the date received at the blood bank. The program created a two-way tabular breakdown by blood type and source of blood to determine the percent of the blood obtained from donors and the percent obtained from the various central sources. The data resulting by this statistical tabulation are shown in Table A3-1.

Analysis of age of blood on receipt

By comparing the date the blood was drawn with the date it was received, the computer program was able to establish its age when it arrived at the blood bank. A table of age of received blood by type was created by the program and is shown in Table A3-2.

Analysis of age of blood on receipt for blood ordered from central sources

The table of age of blood received by blood type included all blood received at the hospital blood bank. To get a true picture of the age of the blood that would be obtained from orders placed with the central sources, the donated blood had to be removed from the tabulation. Table A3-1 shows the number and percent of units of each blood type that were donated and since all donated blood is received fresh at the hospital (age = 0), these units were then deleted from the 0 age category to provide a statistical breakdown of the units received from central sources. These data are shown in Table A3-3.

Analysis of donated blood

In order to determine the frequency of arrival of donated blood, each unit of such blood was tallied on the day it was donated, one tally being kept for each type. This tally was then summarized into a table of number of units of blood donated per day for each blood type. Considering donations to be random events

whose pattern could be described by a Poisson probability distribution, the mean number of donations per day was used as the estimate of the parameter of the Poisson distribution and theoretical models were fit to the data. The theoretical models were tested using the Kolmogorov-Smirnov test of goodness of fit and no evidence was found to reject the Poisson model. The observed data, mean and variance, theoretical Poisson frequencies, the value of the Kolmogorov-Smirnov test statistic ($D_{\max}$) and critical values for this statistic are shown in Table A3-4.

Analysis of Demand at the Blood Bank

In the demand analysis, the basic unit of reference is the patient, not the unit of blood. In order to perform an analysis of the data by patient it was first necessary to sort the transaction file into patient order, with all the transactions for a patient by date order within the patient number. Computer programs were written to perform the following statistical breakdowns so that analysis could be performed to provide the input data for the simulator.

Number of patients per day

In order to determine the frequency of patients requesting blood, each set of transactions for a patient on a given day was taken to be an order for blood on that day. Each order for blood

was tallied on the day it was received at the blood bank, one tally being kept for each blood type. This tally was then summarized into a table of the number of orders (sets of patient requests) for blood per day by blood type. The arrivals of orders were considered to be random events whose pattern could be described by a Poisson probability distribution. The mean number of orders per day was used as the estimate of the parameter of the Poisson distribution and theoretical distributions were fitted to the data. The theoretical models were tested, using the Kolmogorov-Smirnov test of goodness of fit, and no evidence was found to reject the Poisson model. The observed data, mean and variance, theoretical Poisson frequencies, $D_{\max}$, and critical values of $D_{\max}$ are shown in Table A3-5.

Number of units requested
per patient

Having determined the number of patients requesting blood per day, it was necessary to determine the number of units of blood requested by each patient (order size). Since there is one transaction record in the data file for each request for a unit of blood and the data were organized by date within patient, the computer program counted the number of records for a patient on a single day to establish the number of units requested per patient per day. These data were organized by blood type and frequency

distributions of the number of units requested per patient per day were accumulated for each blood type, together with the mean and variance of these distributions. The observed frequency distributions had an excess of observations in the cell corresponding to two units than could be accounted for with any simple statistical model. A composite model was hypothesized which accounted for the relatively high frequency of orders of two units. This model has the following form:

$$f(x) = k g(x) + (1-k) h(x)$$

where $g(x) = 1$, for $x = 2$; $g(x) = 0$, otherwise;

$$h(x) = p(1-p)^{x-1} \text{ for } x \geq 1;$$

k = the probability of order size exactly 2;

$1-k$ = the probability of order size having a geometric probability distribution, $h(x)$.

The parameters of the composite model are k and p , which were estimated from the observed data using the maximum likelihood method. Theoretical frequencies were then established and using the hypothesized model and the Kolmogorov-Smirnov test of goodness of fit did not provide any reason for rejecting the adequacy of this model. The observed and theoretical frequencies, means and variances, estimated parameters, $D_{\max}$ and critical values of $D_{\max}$ are shown in Table A3-6.

Time from request to the cross-
matching and reservation of a unit

At the same time the computer program was counting the number of units in an order, it was also examining the timing of the events in each particular transaction. After the unit is requested, it must be crossmatched against a unit of blood to establish a reservation for the crossmatched unit. The request for a unit is usually made before the unit is actually required to allow time for the crossmatching procedure. The elapsed number of days between request for blood and crossmatching was tallied by blood type to establish frequency distributions of the actual elapsed time. If each day can be viewed as a trial and the elapsed time as the number of trials until success (crossmatch), then a geometric probability distribution can be used as a theoretical model provided an adjustment is made so that elapsed days (i.e. successes) can start at zero. The following model satisfies these conditions:

$$f(x) = p(1-p)^x \text{ where } x \geq 0$$

where p = the probability of success on the first trial (0 elapsed days).

The parameters of these models (one for each blood type) were established from the observed data [$\hat{p} = 1/(\bar{x}+1)$] and the theoretical distributions were fit to the observed data. The Kolmogorov-Smirnov test was again applied and no evidence to reject the theoretical model was found. The observed and theoretical distributions, means,

variances and estimated parameters, and $D_{\max}$ and its critical values are given in Table A3-7.

Number of units requisitioned
(called for) and number of
units returned

As the computer program was accumulating the statistical information on orders and order sizes, it was also able to determine exactly what happened to each of the orders. By examining each of the transactions that comprised an order, the program was able to determine how many of the units originally ordered were eventually requisitioned (called for) and how many of those called for were returned. The number transfused and the number taken off reserve did not have to be tabulated since these statistics can be directly obtained from the previous measures. (Number transfused equals number called for minus number returned and number taken off reserve equals number ordered minus number called for.)

As it was expected that the actual usage characteristics of requisition rate and return rate would be different for different order quantities (especially in light of the model hypothesized for order size generation given in Chapter IV), statistics on number of units returned were accumulated in separate tallies according to the size of the order. In addition, it was anticipated that patient characteristics might affect the usage rates

so that the tallies were also made available by patient types. Examination of the output revealed that order size was in fact an important determinant of usage rate and two types of patients, anemia patients and out-patients, have usage rates markedly different from the overall patient rates. The distributions of numbers of units requisitioned for different order sizes and summary statistics are given for all patients in Chapter IV, Table 10 and the comparable data for the anemia and out-patients are given in Chapter V, Table 17. The distributions of number of units returned for different numbers of units called for and summary statistics are given for all patients in Chapter IV, Table 13 and the comparable data for the anemia and out-patients are given in Chapter V, Table 18.

Timing of the Events in a Transaction Record

In order to generate the events which were generated as part of each transaction (call for, return, or taken off reserve) with the appropriate time delays associated with these events in the simulator, it was necessary to tabulate the observed data according to elapsed days. Thus, as each transaction was examined to determine which events had taken place, the dates which were in the record for the occurrence of the event were used to establish the timing of the event. Thus, if the unit was called for, the difference between the date crossmatched and the date called for was

tallied in a table for time between crossmatch and call for. If the called for unit was returned, then the difference between the date returned and date called for was tallied in a table of time between call for and return. If the unit was not called for, then the difference between the date the reservation was cancelled and the date of the crossmatching was tallied in a table of time from crossmatch to taken off reserve. All the above tables were maintained by blood type so that differences could be evaluated.

Time from crossmatch to call for

The observed data showed that most units are called for on the same day as reserved and almost as many are called for the next day. After that, the number declined very rapidly. A model was hypothesized by first dichotomizing the data into those called for on the same day (0 elapsed days) and those called for after the date crossmatched. If called for after the date crossmatched, a geometric model was used to describe the number of elapsed days. The model has the following form:

$$f(x) = k g(x) + (1-k) h(x)$$

where k = probability of call for on same day as crossmatch;

$1-k$ = probability of not calling for the unit on the same day as it was crossmatched;

$g(x) = 1$, for $x = 0$; $g(x) = 0$, otherwise;

$$h(x) = p(1-p)^{x-1} \text{ for } x \geq 1;$$

p = the probability the unit will be called for the day after it was crossmatched.

The observed data were used to estimate the parameters k and p of this model, using the maximum likelihood method, and theoretical frequencies were obtained using the estimated parameters. The theoretical model was tested for goodness of fit using the Kolmogorov-Smirnov test and no evidence was found to reject the model. The observed and theoretical frequencies, means and variances, estimated parameters, $D_{\max}$ and its critical values are given in Table A3-8.

Time from call for to return

The observed data showed highly "J" shaped distributions for all blood types resembling that of the geometric distribution, except that most returns occurred on the same day as the unit was called for (0 elapsed days). Using the concept that the first opportunity to return occurred on the same day, the second opportunity occurred on the next day, etc., the standard geometric variable was transformed to one applicable in this situation. The model used was as follows:

$$f(x) = p(1-p)^x \text{ for } x \geq 0$$

where x = the elapsed days;

p = the probability of return on the same day ($x = 0$).

Estimates of p were obtained from the observed data and theoretical frequencies were obtained using the hypothesized model. The model was tested for goodness of fit and no evidence was found to reject it. The observed and theoretical frequencies, means, variances and estimated parameters, $D_{\max}$ and its critical values are all shown in Table A3-9.

Time from crossmatch to
taken off reserve

Examination of the time between crossmatch and taken off reserve revealed an abnormally high peak at two days. Since this is the elapsed time that would occur when the blood bank followed its standard rules for the maximum duration of a reservation, a model was hypothesized which recognized that either the standard, two-day period applied or it did not; and if not, then the elapsed time could be characterized by a geometric distribution. The model takes on the following form:

$$f(x) = k g(x) + (1-k) h(x)$$

where k = the proportion of the time the standard rule is applied;

$1-k$ = the proportion of time it is not applied;

$g(x) = 1$, for $x = 2$; $g(x) = 0$, otherwise; *

$h(x) = p(1-p)^{x-1}$ for $x \geq 1$;

p = the probability of taken off reserve at the first opportunity (day after crossmatch).

The observed data were used to estimate the parameters k and p of this model, using the maximum likelihood method. Theoretical frequencies were calculated using the model with the estimated parameters. The Kolmogorov-Smirnov test of goodness of fit did not give any reason to indicate the model was not appropriate. The observed and theoretical frequencies, means, variances and estimated parameters, together with the measures relative to the goodness of fit test, are given in Table A3-10.

TABLE A3-1

ANALYSIS OF NUMBER OF UNITS RECEIVED BY TYPE AND SOURCE

Source	Blood Type							
	A+		A-		B+		B-	
	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent
Walking Blood Bank	45	3.11	6	2.61	10	1.88	1	1.75
Donor-Polycythemia	10	0.69	1	0.43	2	0.38	0	0.00
Donor	179	12.38	36	15.65	63	11.84	11	19.30
Red Cross	305	21.09	46	20.00	96	18.05	6	10.53
N.Y. Blood Center	255	17.63	44	19.13	110	20.68	6	10.53
Pioneer Blood Bank	111	7.68	28	12.17	61	11.47	9	15.79
National Blood Bank	78	5.39	9	3.91	6	1.13	5	8.77
Elmhurst Hospital	11	0.76	4	1.74	11	2.07	3	5.26
Inter-County Blood Bank	23	1.59	0	0.00	0	0.00	1	1.75
Pfizer Diagnostics	19	1.31	5	2.17	23	4.32	5	8.77
Greater New York Blood Program	407	28.15	49	21.30	150	28.20	8	14.04
Empire Blood Bank	3	0.21	2	0.87	0	0.00	2	3.51
Other	0	0.00	0	0.00	0	0.00	0	0.00
TOTAL	1446	100.00	230	100.00	532	100.00	57	100.00

TABLE A3-1--continued

Source	Blood Type							
	AB+		AB-		O+		O-	
	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent
Walking Blood Bank	2	1.01	0	0.00	40	2.42	4	2.68
Donor-Polycythemia	8	4.02	0	0.00	15	0.91	1	0.67
Donor	28	14.07	9	15.79	207	12.54	31	20.81
Red Cross	34	17.09	12	21.05	367	22.23	11	7.38
N.Y. Blood Center	45	22.61	14	24.56	299	18.11	24	16.11
Pioneer Blood Bank	18	9.05	7	12.28	117	7.09	29	19.46
National Blood Bank	11	5.53	1	1.75	54	3.27	7	4.70
Elmhurst Hospital	4	2.01	2	3.51	9	0.55	4	2.68
Inter-County Blood Bank	1	0.50	0	0.00	10	0.61	0	0.00
Pfizer Diagnostics	6	3.02	0	0.00	46	2.79	5	3.36
Greater New York Blood Program	42	21.11	12	21.05	483	29.25	29	19.46
Empire Blood Bank	0	0.00	0	0.00	4	0.24	4	2.68
Other	0	0.00	0	0.00	0	0.00	0	0.00
TOTAL	199	100.00	57	100.00	1651	100.00	149	100.00

TABLE A3-2

AGE OF BLOOD ON RECEIPT BY TYPE FOR ALL SOURCES COMBINED

No. of Days	Blood Type							
	A+		A-		B+		B-	
	Percent	Cum. Pct	Percent	Cum. Pct.	Percent	Cum. Pct	Percent	Cum. Pct.
0	18.67	18.7	19.13	19.1	14.66	14.7	22.81	22.8
1	9.41	28.1	9.13	28.3	6.95	21.6	14.04	36.8
2	9.06	37.1	16.96	45.2	5.64	27.3	14.04	50.9
3	5.88	43.0	10.00	55.2	6.58	33.8	3.51	54.4
4	3.80	46.8	15.65	70.9	7.33	41.2	14.04	68.4
5	3.94	50.8	6.09	77.0	12.41	53.6	12.28	80.7
6	5.46	56.2	6.09	83.0	8.27	61.8	8.77	89.5
7	9.75	66.0	5.22	88.3	5.64	67.5	1.75	91.2
8	6.98	73.0	3.91	92.2	10.15	77.6	1.75	93.0
9	5.81	78.8	3.48	95.7	5.08	82.7	0.00	93.0
10	3.39	82.2	1.30	97.0	7.52	90.2	3.51	96.5
11	4.15	86.3	1.30	98.3	2.63	92.9	0.00	96.5
12	4.91	91.2	0.00	98.3	2.63	95.5	0.00	96.5
13	4.15	95.4	0.87	99.1	1.88	97.4	0.00	96.5
14	2.42	97.8	0.43	99.6	1.13	98.5	0.00	96.5
15	1.04	98.8	0.00	99.6	0.19	98.7	0.00	96.5
16	1.04	99.9	0.43	100.0	0.00	98.7	3.51	100.0
17	0.14	100.0			0.19	98.9		
18					0.38	99.2		
19					0.75	100.0		
Mean	5.5007		3.5348		5.4831		3.4035	
Variance	20.8827		9.6298		16.2539		12.6021	
Std. Dev.	4.5698		3.1032		4.0316		3.5500	
No. of Obs.	1446		230		532		57	

TABLE A3-2--continued

No. of Days	Blood Type							
	AB+		AB-		O+		O-	
	Percent	Cum.Pct.	Percent	Cum.Pct.	Percent	Cum.Pct.	Percent	Cum.Pct.
0	20.60	20.6	35.09	35.1	17.50	17.5	26.17	26.2
1	8.54	29.1	8.77	43.9	5.33	22.8	16.78	43.0
2	20.60	49.7	21.05	64.9	7.87	30.7	20.13	63.1
3	9.05	58.8	3.51	68.4	6.72	37.4	18.79	81.9
4	10.05	68.8	10.53	78.9	4.24	41.7	6.04	87.9
5	8.04	76.9	7.02	86.0	3.63	45.3	5.37	93.3
6	7.04	83.9	10.53	96.5	10.54	55.8	0.00	93.3
7	4.02	87.9	0.00	96.5	9.45	65.3	1.34	94.6
8	3.02	91.0	1.75	98.2	10.48	75.8	0.67	95.3
9	2.51	93.5	1.75	100.0	4.18	80.0	0.67	96.0
10	2.51	96.0			2.67	82.6	0.00	96.0
11	1.51	97.5			5.39	88.0	0.00	96.0
12	0.50	98.0			3.21	91.2	0.00	96.0
13	0.00	98.0			4.42	95.6	2.01	98.0
14	0.00	98.0			2.00	97.6	1.34	99.3
15	1.01	99.0			1.27	98.9	0.67	100.0
16	0.50	99.5			1.03	99.9		
17	0.50	100.0			0.06	100.0		
Mean	3.5377		2.3158		5.7371		2.4027	
Variance	11.4115		5.7556		19.0460		8.4313	
Std.Dev.	3.3781		2.3991		4.3642		2.9037	
No. of Obs.	199		57		1651		149	

TABLE A3-3
AGE OF BLOOD ON RECEIPT BY TYPE FROM OUTSIDE SOURCES

No. of Days	Blood Type							
	A+		A-		B+		B-	
	Percent	Cum. Pct.	Percent	Cum. Pct.	Percent	Cum. Pct.	Percent	Cum. Pct.
0	2.97	2.97	0.54	0.54	0.65	0.65	2.23	2.23
1	11.23	14.20	11.23	11.77	8.09	8.74	17.78	20.01
2	10.80	25.00	20.86	32.63	6.57	15.31	17.78	37.79
3	7.02	32.02	12.30	44.93	7.66	22.97	4.45	42.24
4	4.53	36.55	19.25	64.18	8.53	31.50	17.78	60.02
5	4.70	41.25	7.49	71.67	14.45	45.95	15.55	75.57
6	6.51	47.76	7.49	79.16	9.63	55.58	11.11	86.68
7	11.63	59.39	6.42	85.58	6.57	62.15	2.22	88.90
8	8.33	67.72	4.81	90.39	11.82	73.97	2.22	91.12
9	6.93	74.65	4.28	94.67	5.91	79.88	0.00	91.12
10	4.04	78.69	1.60	96.27	8.75	88.63	4.45	95.57
11	4.95	83.64	1.60	97.87	3.06	91.69	0.00	95.57
12	5.86	89.50	0.00	97.87	3.06	94.75	0.00	95.57
13	4.95	94.45	1.07	98.94	2.19	96.94	0.00	95.57
14	2.89	97.34	0.53	99.47	1.32	98.26	0.00	95.57
15	1.24	98.59	0.00	99.47	0.22	98.48	0.00	95.57
16	1.24	99.82	0.53	100.00	0.00	98.49	4.43	100.00
17	0.18	100.00			0.22	98.70		
18					0.44	99.14		
19					0.86	100.00		
Mean	6.5647		4.3459		6.3823		4.3090	
Variance	17.9637		8.2910		13.1517		12.0204	
No. of Obs.	1212		187		457		45	

TABLE A3-3--continued

No. of Days	Blood Type							
	AB+		AB-		O+		O-	
	Percent	Cum. Pct.	Percent	Cum. Pct.	Percent	Cum. Pct.	Percent	Cum. Pct.
0	1.85	1.85	22.92	22.92	1.94	1.94	2.65	2.65
1	10.56	12.41	10.41	33.33	6.34	8.28	22.13	24.78
2	25.46	37.87	25.00	58.33	9.35	17.63	26.54	51.32
3	11.19	49.06	4.17	62.50	7.99	25.62	24.78	76.10
4	12.42	61.48	12.50	75.00	5.04	30.66	7.96	84.06
5	9.94	71.42	8.34	83.34	4.31	34.97	7.08	91.14
6	8.70	80.12	12.50	95.84	12.53	47.50	0.00	91.14
7	4.97	85.09	0.00	95.84	11.23	58.73	1.77	92.91
8	3.73	88.82	2.08	97.92	12.46	71.19	0.88	93.79
9	3.10	91.92	2.08	100.00	4.97	76.16	0.88	94.67
10	3.10	95.02			3.17	79.33	0.00	94.67
11	1.87	96.89			6.41	85.74	0.00	94.67
12	0.62	97.51			3.82	89.56	0.00	94.67
13	0.00	97.51			5.25	94.81	2.65	97.32
14	0.00	97.51			2.38	97.19	1.77	99.09
15	1.25	98.76			1.51	98.70	0.91	100.00
16	0.62	99.38			1.22	99.92		
17	0.62	100.00			0.08	100.00		
18								
19								
Mean	4.3738		2.7498		6.8207		3.1702	
Variance	10.4506		5.6364		15.2591		8.7222	
No. of Obs.	161		48		1389		113	

TABLE A3-4

NUMBER OF UNITS DONATED PER DAY BY BLOOD TYPE
THEORETICAL MODEL: POISSON^a

No. of Units	Blood Type							
	A+		A-		B+		B-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct.)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	15.38	11.65	75.47	69.77	51.40	49.66	89.72	89.58
1	28.85	25.05	16.04	25.11	30.84	34.76	9.35	9.86
2	16.35	26.92	6.60	4.52	14.95	12.17	0.93	0.54
3	20.19	19.29	0.94	0.55	1.87	2.84		0.02
4	9.62	10.37	0.94	0.05	0.94	0.50		
5	4.81	4.46				0.07		
6	2.88	1.60				0.01		
7	1.92	0.49						
8		0.13						
9		0.03						
10		0.01						
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	104		106		107		107	
Mean	2.1540	2.1540	0.3585	0.3585	0.7009	0.7009	0.1122	0.1122
Variance	2.8693	2.1540	0.5319	0.3585	0.7399	0.7009	0.1183	0.1122
D _{max}	.0754		.0570		.0218		.0037	
Critical D _{max} :								
σ = .05	.1334		.1321		.1315		.1315	
σ = .20	.1049		.1039		.1034		.1034	

^a $f(x) = e^{-u} u^x / x!$

TABLE A3-4--continued

No. of Units	Blood Type							
	AB+		AB-		O+		O-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	72.90	69.77	98.10	98.02	14.02	8.46	73.83	70.47
1	20.56	25.11	1.90	1.96	18.69	20.89	18.69	24.66
2	4.67	4.52		0.02	22.43	25.80	6.54	4.32
3	1.87	0.55			17.76	21.24	0.93	0.50
4		0.05			14.95	13.12		0.05
5					6.54	6.48		
6					2.80	2.67		
7					1.87	0.94		
8					0.93	0.29		
9						0.09		
10						0.02		
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	107		105		107		107	
Mean	0.3551	0.3551	0.0190	0.0190	2.4673	2.4673	0.3458	0.3458
Variance	0.4576	0.3551	0.0187	0.0190	3.1758	2.4673	0.4131	0.3458
D _{max}	.0313		.0008		.0556		.0336	
Critical D _{max} :								
$\alpha = .05$	.1315		.1327		.1315		.1315	
$\alpha = .20$	.1034		.1044		.1034		.1034	

TABLE A3-5a

NUMBER OF PATIENTS PER DAY - SUNDAY TO THURSDAY
THEORETICAL MODEL: POISSON^a

No. of Pat.	Blood Type							
	A+		A-		B+		B-	
	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)
0		0.00	14.13	13.94	2.90	0.20	50.00	53.26
1		0.00	24.11	27.47	1.45	1.20	38.57	33.55
2		0.00	38.72	27.07	1.45	3.80	8.57	10.57
3		0.01	8.33	17.78	7.25	7.90	2.86	2.22
4		0.04	10.30	8.76	11.59	12.30		0.35
5		0.13	2.94	3.45	11.59	15.40		0.05
6		0.34	1.47	1.13	21.74	16.00		
7		0.76		0.32	11.59	14.20		
8	2.90	1.47		0.08	10.14	11.20		
9	4.35	2.55			10.14	7.70		
10	4.35	3.98			1.45	4.80		
11	8.70	5.63			1.45	2.70		
12	7.25	7.31			5.80	1.40		
13	10.14	8.77				0.70		
14	5.80	9.76				0.30		
15	7.25	10.13				0.10		
16	7.25	9.87				0.10		
17	10.14	9.04						
18	8.70	7.83						
19	4.35	6.42						
20	8.70	5.00						
21	0.00	3.71						
22	0.00	2.63						
23	4.35	1.78						
24	2.90	1.15						
25	0.00	0.72						
26	1.45	0.43						
27	1.45	0.30						
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	69		68		69		70	
Mean	15.580	15.580	1.971	1.971	6.235	6.235	0.629	0.629
Variance	19.630	15.580	1.850	1.971	7.138	6.235	0.599	0.629
D _{max}	.067		.085		.039		.033	
Critical D _{max} :								
α = .05	.160		.160		.160		.160	
α = .20	.129		.130		.129		.128	

^a $f(x) = e^{-u} u^x / x!$

TABLE A3-5a--continued

No. of Pat.	Blood Type							
	AB+		AB-		O+		O-	
	Obs Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)
0	7.14	9.44	62.86	67.03		0.00	17.14	15.11
1	21.43	22.29	34.28	26.81		0.00	28.57	28.55
2	22.86	26.29	2.86	5.36		0.00	27.15	26.98
3	35.71	20.69		0.72		0.00	11.43	17.00
4	7.15	12.20		0.08		0.02	8.57	8.03
5	2.85	5.76				0.05	5.71	3.03
6	1.43	2.26				0.15	1.43	0.97
7	1.43	0.77			1.45	0.37		0.25
8		0.22			0.00	0.77		0.08
9		0.08			0.00	1.45		
10					4.35	2.44		
11					4.35	3.74		
12					5.80	5.25		
13					8.70	6.81		
14					4.35	8.20		
15					4.35	9.21		
16					13.04	9.71		
17					7.25	9.62		
18					13.04	9.01		
19					7.25	7.99		
20					4.35	6.74		
21					5.80	5.41		
22					11.59	4.14		
23					1.45	3.04		
24					1.45	2.13		
25					0.00	1.44		
26					0.00	0.93		
27					1.45	0.58		
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	70		70		69		70	
Mean	2.357	2.357	0.400	0.400	16.855	16.855	1.886	1.886
Var.	1.885	2.357	0.301	0.400	16.214	16.855	2.190	1.886
D _{max}	.084		.042		.052		.033	
Critical D _{max} :								
$\alpha = .05$	.160		.160		.160		.160	
$\alpha = .20$	.128		.128		.129		.129	

TABLE A3-5b

NUMBER OF PATIENTS PER DAY - FRIDAY AND SATURDAY
THEORETICAL MODEL: POISSON^a

No. of Pat.	Blood Type							
	A+		A-		B+		B-	
	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)
0		0.00	25.00	24.91	0.00	2.26	57.14	63.13
1		0.09	32.14	34.62	7.14	8.57	39.29	29.04
2		0.40	28.57	24.06	21.43	16.23	3.57	6.68
3		1.23	7.14	11.15	21.43	20.50		1.02
4		2.87	7.14	3.87	17.86	10.43		0.12
5	10.71	5.33		1.08	17.86	14.72		0.01
6	10.71	8.25		0.25	3.57	9.30		
7	3.57	10.94		0.05	3.57	5.03		
8	21.43	12.71		0.01	7.14	2.39		
9	7.14	13.12				1.00		
10	7.14	12.18				0.38		
11	17.86	10.29				0.13		
12	10.71	7.96				0.04		
13	3.57	5.69				0.01		
14	3.57	3.78						
15	0.00	2.34						
16	3.57	1.36						
17		0.74						
18		0.38						
19		0.19						
20		0.08						
21		0.03						
22		0.02						
23		0.01						
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	28		28		28		28	
Mean	9.286	9.286	1.393	1.393	3.786	3.786	0.464	0.464
Var.	8.201	9.286	1.358	1.393	3.582	3.786	0.333	0.464
D _{max}	.064		.024		.040		.060	
Critical D _{max} :								
α = .05	.242		.242		.242		.242	
α = .20	.190		.190		.190		.190	

^a $f(x) = e^{-u} u^x / x!$

TABLE A3-5b--continued

No. of	Blood Type							
	AB+		AB-		O+		O-	
	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel. Freq. (Pct)	Theor Prob. (Pct)
0	35.71	24.91	92.86	89.58		0.01	28.57	27.53
1	28.57	34.62	3.57	9.85		0.13	32.14	35.51
2	10.71	24.06	3.57	0.54		0.58	21.43	22.90
3	14.29	11.15		0.02		1.70	17.86	9.85
4	7.14	3.87				3.75		3.18
5	3.57	1.08			7.69	6.60		0.82
6		0.25			11.54	9.69		0.18
7		0.05			7.69	12.20		0.03
8		0.01			30.77	13.43		0.01
9					15.38	13.15		
10					3.85	11.58		
11					11.54	9.28		
12					0.00	6.81		
13					0.00	4.61		
14					7.69	2.90		
15					0.00	1.71		
16					3.85	0.94		
17						0.49		
18						0.24		
19						0.11		
20						0.05		
21						0.02		
22						0.01		
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	28		28		28		28	
Mean	1.393	1.393	0.107	0.107	8.808	8.808	1.286	1.286
Var.	2.173	1.393	0.173	0.107	7.442	8.808	1.175	1.286
D _{max}	.108		.034		.119		.038	
Critical D _{max} :								
$\alpha = .05$	.242		.242		.242		.242	
$\alpha = .20$	.190		.190		.190		.190	

TABLE A3-6

NUMBER OF UNITS REQUESTED PER PATIENT PER DAY
 THEORETICAL MODEL: $f(x) = k g(x) + (1-k) h(x)^*$

No. of Units	Blood Type							
	A+		A-		B+		B-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
1	30.8	30.93	30.8	29.99	33.4	33.83	53.9	54.98
2	50.6	50.43	54.4	54.24	46.3	46.32	36.5	36.50
3	8.8	8.73	6.2	7.75	9.7	9.40	7.7	5.76
4	5.6	4.64	5.6	3.94	6.7	4.95	1.9	1.87
5	1.4	2.47	0.5	2.00	1.8	2.61		0.60
6	1.6	1.31	1.5	1.02	0.9	1.37		0.20
7	0.2	0.70	0.0	0.52	0.0	0.72		0.07
8	0.3	0.37	0.5	0.26	0.5	0.38		0.02
9	0.1	0.20	0.0	0.13	0.0	0.20		
10	0.1	0.11	0.0	0.07	0.0	0.11		
10+	0.4	0.40	0.5	0.08	0.7	0.11		
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	1352		195		566		52	
Mean	2.0880	2.0880	2.0205	2.0205	2.0813	2.0813	1.5762	1.5762
Variance	1.6777	1.5992	1.4944	1.2826	1.7598	1.6858	0.5234	0.6171
K	---	.340	---	.390	---	.285	---	.187
P	---	.4687	---	.4917	---	.4731	---	.6762
D _{max}	.0107		.0098		.0160		.0113	
Critical D _{max} :								
$\alpha = .05$	.0370		.097		.057		.190	
$\alpha = .20$	.0291		.077		.045		.148	

* $g(x) = 1$ for $x = 2$, $g(x) = 0$, otherwise.
 $h(x) = p(1-p)^{x-1}$ for $x \geq 1$.

TABLE A3-6--continued

No. of Units	Blood Type							
	AB+		AB-		O+		O-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
1	38.1	36.22	47.8	47.92	26.4	27.62	29.2	26.92
2	44.3	44.26	43.5	43.46	50.7	50.72	49.1	49.11
3	8.1	9.51	4.3	5.67	10.9	9.18	7.0	9.63
4	5.2	4.81	4.3	1.95	6.0	5.29	4.1	5.76
5	1.9	2.50		0.67	2.3	3.05	3.5	3.44
6	0.5	1.28		0.23	1.8	1.76	4.7	2.06
7	0.0	0.65		0.10	0.5	1.02	0.0	1.23
8	0.5	0.33			0.6	0.59	1.2	0.74
9	0.0	0.17			0.2	0.34	0.0	0.44
10	0.0	0.09			0.1	0.20	0.0	0.26
10+	1.4	0.18			0.5	0.23	1.2	0.41
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	210		23		1483		171	
Mean	2.0381	2.0381	1.6522	1.6522	2.2353	2.2353	2.3275	2.3275
Variance	2.2569	1.6028	0.6008	0.6272	1.9668	2.1239	2.8686	2.5354
K	---	.257	---	.270	---	.348	---	.330
P	---	.4875	---	.6565	---	.4236	---	.4018
D _{max}	.0192		.0135		.0124		.0237	
Critical D _{max} :								
$\alpha = .05$	.094		.264		.035		.104	
$\alpha = .20$	.074		.22		.028		.082	

TABLE A3-7

TIME FROM REQUEST TO CROSSMATCH - MODEL: SHIFTED GEOMETRIC^a

	Blood Type							
	A+		A-		B+		B-	
No. of Days	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	87.6	88.0	90.4	90.7	88.1	88.7	86.5	87.1
1	11.5	10.5	9.0	8.4	11.1	10.0	12.2	11.3
2	0.7	1.3	0.6	0.8	0.8	1.1	1.3	1.5
3	0.2	0.2		0.1		0.2		0.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	2568		343		1209		74	
Mean	0.1359	0.1359	0.1020	0.1020	0.1274	0.1274	0.1486	0.1486
Variance	0.1463	0.1544	0.1036	0.1125	0.1278	0.1436	0.1557	0.1707
P	---	.8804	---	.9074	---	.8870	---	.8706
D _{max}	.006		.003		.006		.006	
Critical D _{max} :								
α = .05	.027		.073		.039		.150	
α = .20	.021		.058		.030		.124	

^a $g(x) = p(1-p)^x$ for $x \geq 0$.

TABLE A3-7--continued

	Blood Type							
	AB+		AB-		O+		O-	
No. of Days	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	83.8	84.3	81.1	80.4	89.1	88.9	86.1	85.4
1	14.6	13.2	16.2	15.7	10.0	9.8	11.0	12.4
2	0.8	2.1	0.0	3.1	0.8	1.1	2.6	1.8
3	0.8	0.3	2.7	0.6	0.1	0.1	0.3	0.3
4		0.1		0.2	0.0	0.1		0.1
5					0.1			
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	371		37		3355		317	
Mean	0.1860	0.1860	0.2432	0.2432	0.1237	0.1237	0.1703	0.1703
Variance	0.2167	0.2206	0.3559	0.3024	0.1532	0.1390	0.2114	0.1994
P	---	.8432	---	.8043	---	.8899	---	.8544
D _{max}	.009		.019		.004		.007	
Critical D _{max} :								
$\alpha = .05$	.071		.210		.024		.076	
$\alpha = .20$	.056		.180		.018		.060	

TABLE A3-8

TIME FROM CROSSMATCH TO CALL FOR
THEORETICAL MODEL: $f(x) = k g(x) + (1-k) h(x) *$

No. of Days	Blood Type							
	A+		A-		B+		B-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	59.4	59.4	63.2	63.2	58.8	58.8	60.5	60.5
1	35.3	35.2	32.5	32.0	35.1	34.5	39.5	39.5
2	4.6	4.7	3.7	4.2	4.8	5.6		
3	0.6	0.6	0.0	0.6	0.9	0.9		
4	0.1	0.1	0.6	0.1	0.4	0.2		
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	1080		163		561		43	
Mean	0.4685	0.4685	0.4233	0.4233	0.4884	0.4884	0.3953	0.3953
Variance	0.3920	0.3912	0.3938	0.3707	0.4432	0.4385	0.2447	0.2390
K	---	.594	---	.632	---	.588	---	.605
P	---	.868	---	.870	---	.839	---	1.000
D _{max}	.001		.014		.014		.000	
Critical D _{max} :								
$\alpha = .05$	.041		.107		.057		.200	
$\alpha = .20$	.033		.084		.045		.163	

* $g(x) = 1$, for $x_1 = 0$, $g(x) = 0$ otherwise.
 $h(x) = p(1-p)^{x-1}$ for $x \geq 1$.

TABLE A3-8--continued

No. of Days	Blood Type							
	AB+		AB-		O+		O-	
	Obs. Rel.Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	62.6	62.6	81.8	81.8	57.3	57.3	70.3	70.3
1	34.1	32.4	18.2	18.2	36.6	36.2	25.8	24.6
2	2.2	4.3			5.1	5.5	1.6	4.2
3	0.6	0.6			0.8	0.9	2.3	0.7
4	0.0	0.1			0.2	0.1		0.2
5	0.6			0.1				
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	179		11		1441		128	
Mean	0.4302	0.4302	0.1818	0.1818	0.5038	0.5038	0.3594	0.3594
Variance	0.4375	0.3790	0.1636	0.1489	0.4404	0.4313	0.4053	0.3793
K	---	.626	---	.818	---	.573	---	.703
P	---	.866	---	1.000	---	.848	---	.828
D _{max}	.043		.000		.007		.048	
Critical D _{max} :								
$\sigma = .05$	.102		.391		.036		.120	
$\sigma = .20$	.080		.307		.028		.095	

TABLE A3-9

TIME FROM CALL FOR TO RETURN
THEORETICAL MODEL: SHIFTED GEOMETRIC^a

	Blood Type							
	A+		A-		B+		B-	
No. of Days	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	80.5	80.2	82.9	85.4	83.1	78.3	88.9	90.0
1	16.5	15.9	17.1	12.5	10.8	17.0	11.1	9.0
2	2.1	3.1		2.1	1.4	3.7		1.0
3	0.9	0.6			4.7	0.8		
4	0.0	0.1				0.2		
5	0.4	0.1						
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	329		41		152		9	
Mean	0.2462	0.2462	0.1707	0.1707	0.2770	0.2770	0.1111	0.1111
Variance	0.3447	0.3068	0.1451	0.1999	0.5146	0.3540	0.1111	0.1235
P		.802		.854		.783		.900
D _{max}	.005		.025		.048		.011	
Critical D _{max} :								
$\alpha = .05$	.075		.210		.112		.432	
$\alpha = .20$	.059		.167		.087		.339	

^a $f(x) = p(1-p)^x$ for $x \geq 0$.

TABLE A3-9--continued

	Blood Type							
	AB+		AB-		O+		O-	
No. of Days	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
0	86.7	80.0	100.0	100.0	78.9	80.4	63.0	73.0
1	6.7	16.0			18.8	15.8	37.0	19.7
2	1.7	3.2			1.5	3.1		5.3
3	5.0	0.6			0.5	0.6		1.5
4		0.2			0.3	0.1		0.4
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Obs.	60		3		398		27	
Mean	0.2500	0.2500	0.000	0.000	0.2437	0.2437	0.3695	0.3695
Variance	0.5297	0.3125	0.000	0.000	0.2755	0.3031	0.2422	0.5075
P		.800		1.000		.804		.730
D _{max}	.067		.000		.015		.100	
Critical D _{max} :								
$\alpha = .05$	.170		.708		.068		.242	
$\alpha = .20$	.138		.565		.054		.190	

TABLE A3-10

TIME FROM CROSSMATCH TO TAKEN OFF RESERVE
 THEORETICAL MODEL: $f(x) = k g(x) + (1-k) h(x)^*$

No. of Days	Blood Type							
	A+		A-		B+		B-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
1	8.00	9.83	12.33	12.49	14.26	17.05	7.20	8.68
2	83.69	83.70	82.61	82.60	74.36	74.36	85.71	85.70
3	5.27	2.93	2.83	2.65	9.14	4.28	3.54	2.56
4	2.03	1.60	1.72	1.22	1.60	2.15	3.54	1.39
5	0.71	0.88	0.00	0.56	0.48	1.08		0.76
6	0.20	0.48	0.00	0.26	0.16	0.54		0.41
7		0.26	0.51	0.12		0.27		0.22
8		0.14		0.06		0.15		0.12
9		0.08				0.08		
10						0.04		
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	1462		178		624		28	
Mean	2.0390	2.0390	2.0441	2.0441	2.0016	2.0016	2.0362	2.0362
Variance	0.3156	0.5819	0.2066	0.3759	0.3676	0.6888	0.2569	0.5013
K		.7833		.7685		.6581		.8098
P		.4538		.5396		.4988		.4566
$D_{\max}$	.017		.005		.028		.015	
Critical $D_{\max}$:								
$\alpha = .05$	.036		.102		.054		.242	
$\alpha = .20$	.028		.080		.043		.190	

* $g(x) = 1$ for $x = 2$, $g(x) = 0$ otherwise.
 $h(x) = p(1-p)^{x-1}$ for $x \geq 1$.

TABLE A3-10--continued

No. of Days	Blood Type							
	AB+		AB-		O+		O-	
	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)	Obs. Rel.Freq. (Pct)	Theor. Prob. (Pct)
1	10.62	11.93	17.40	17.40	11.36	13.02	13.99	16.14
2	81.92	81.90	82.60	82.26	79.01	79.01	75.79	75.80
3	5.31	3.05		0.29	6.19	3.71	8.58	4.03
4	1.63	1.54		0.04	1.83	1.98	0.51	2.02
5	0.00	0.78		0.01	1.22	1.06	0.00	1.01
6	0.00	0.40			0.20	0.56	1.13	0.50
7	0.51	0.20			0.10	0.30		0.25
8		0.10			0.09	0.16		0.13
9						0.11		
10						0.09		
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Obs.	188		23		1894		186	
Mean	2.0056	2.0056	1.8253	1.8253	2.0407	2.0407	1.9999	1.9999
Variance	0.3577	0.4996	0.1517	0.1608	0.4589	0.6911	0.4218	0.6450
K		.7587		.8000		.7206		.6773
P		.4943		.8700		.4661		.5001
D _{max}	.013		.006		.017		.024	
Critical D _{max} :								
$\alpha = .05$	.099		.280		.031		.100	
$\alpha = .20$	.078		.210		.024		.079	

APPENDIX IV

HOSPITAL BLOOD BANK SIMULATOR

PROGRAM LISTING

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C      HOSPITAL BLOOD BANK INVENTORY SIMULATOR
C      PROGRAMMED BY M. RABINOWITZ
C      OPERATIONS RESEARCH DEPT., 19 E. 98 ST., X8582
      IMPLICIT INTEGER*2 (I-N)
      INTEGER IY, IDATA, IJK
      DIMENSION IY(120)
      COMMON IY, NLM, IAGE, IDATE, IUNIT, IBT, N1, N2, I1, IDPAT, NX, NCF, IDCF, NRE
X, IDRET, IDTOR, ICF, YNRET, YNCF
      COMMON IV(125,3), IBEG(9), NI(8), INV(500,13), IREQ(9)
      COMMON/A/ XTAB(6,25,8), CUM(9), XTOR(2,8),
      1XORDAG(22,8), XNDR(8), XNPAT(2,8), REQXM(8), XNUNT(2,8), XNCF(11,10),
      2XCF(2,8), XNRET(11,10), XRET(8), NMAX(8), IOD(9), ITRANS(9), KNT(9),
      3IDMD(200,4), NOUT(8), IDES(8)
      DIMENSION XINVN(2,8), XINVAG(22,8), RSVPB(8),
      1PAGE(8), HEAD(16), BTYPE(9)
      2, SUBHED(16), COLHD1(16), COLHD2(16), TABHED(16,7), IDATA(8)
      EQUIVALENCE (XINVAG(1,1), XORDAG(1,1)), (XINVN(1,1), XNPAT(1,1)),
      1(REQXM(1), RSVPB(1)), (IDATA(1), CUM(1)), (PAGE(1), XNDR(1)), (HEAD(1),
      2XINVN(1,1)), (SUBHED(1), XTOR(1,1)), (BTYPE(1), XNCF(1,1)), (COLHD1(1),
      3XNUNT(1,1)), (COLHD2(1), XCF(1,1)), (TABHED(1,1), XORDAG(1,1))
      COMMON/B/ NUNIT, ND, NDPAT, NDAYS, IJK
      COMMON/D/ IABLE(8)
      ND=0
      CALL BEGIN
      GO TO 750
C      ORDERING OF BLOOD AND RECEIPT OF DONATIONS
100  NLM=0
      IJK=IDATE+1
      IF (MOD(IJK,7).LT.2) GO TO 140
      DO 130 IBT=1,8
      NDES=IDES(IBT)
      IDATA(IBT)=0
      IJK=IDATE
      IF (MOD(IJK,7).EQ.5) NDES=NDES*1.1
      NN=N(IBT)-NOUT(IBT)
      IF (NDES.LE.NN) GO TO 130
      NREC=NDES-NN
      IDATA(IBT)=NREC
      N1=NLM+1
      N2=N1+NREC-1
      NLM=NLM+NREC
      IF (NLM.LE.125) GO TO 105
      K=50+IBT
      GO TO 890
105  DO 120 I=N1,N2
      IJK=I-N1+1
      IF (MOD(IJK,5).NE.1) GO TO 115
      J=15*IBT-14
      CALL RANDU(IY(J),RN)
      DO 110 J=1,22
      IF (RN.GE.XORDAG(J,IBT)) GO TO 110
      IAGE=IDATE+1-J
      GO TO 115
110  CONTINUE
115  IUNIT=IUNIT+1
      IV(1,1)=IUNIT

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      IV(1,2)=IAGE
      IV(1,3)=IBT
120  CONTINUE
130  CONTINUE
C    WRITE(3,135)IDATA
C 135  FORMAT(14HORDERED BLOOD,6X,8I8)
C    RECEIPT OF DONATIONS
140  DO 170 IBT=1,8
      IDATA(IBT)=0
C      IF(IY(2).NE.0)GO TO 142
C      NX= XNDNR(IBT)+0.5
C      GO TO 145
142  NX=15*IBT-13
      CALL POIS(XNDNR(IBT),NX)
145  IF(NX.LE.0) GO TO 170
      N1= IBEG(IBT)+N(IBT)
      N2= N1+NX-1
      IDATA(IBT)=NX
      DO 160 J= N1,N2
        IUNIT=IUNIT+1
        INV(J,1)=IUNIT
        INV(J,2)=IDATE
        INV(J,3)=IDATE
      DO 150 K=4,13
150  INV(J,K)=0
160  CONTINUE
      N(IBT)=N(IBT)+NX
      IF(IBEG(IBT)+N(IBT).GE.IBEG(IBT+1))GO TO 889
170  CONTINUE
C    WRITE(3,175)IDATA
C 175  FORMAT(10HODONATIONS,10X,8I8)
C    GENERATION OF REQUEST SLIPS
      K=1
      IJK=IDATE
      IF (MOD(IJK,7).GE.5) K=2
      DO 220 IBT=1,8
        IDATA(IBT)=0
C      IF(IY(3).NE.0)GO TO 180
C      NX= XNPAT(K,IBT)+0.5
C      GO TO 185
180  NX=15*IBT-12
      CALL POIS(XNPAT(K,IBT),NX)
185  IF(NX.LE.0) GO TO 220
      N1=ND+1
      N2=ND+NX
      ND=ND+NX
      IDATA(IBT)=NX
      PCTSP=XNCF(11,9)
      NY=0
      IF(PCTSP.LE.0.0) GO TO 200
      NY=15*IBT-11
      XNP=PCTSP*NX
      XNPQ=XNP*(1.0-PCTSP)
      CALL BIN(XNP,XNPQ,NY)
200  N3=N1+NY
      DO 210 I=N1,N2

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NDPAT=NDPAT+1
IF(NDPAT.GT.3000) NDPAT=1
IDMD(1,1)=NDPAT*10+IBT
IF(1.LT.N3) IDMD(1,1)=-IDMD(1,1)
IDMD(1,2)=IDATE
C IF(IY(5).NE.0)GO TO 202
C IDMD(1,3)=IDATE
C GO TO 204
202 NX=15*IBT-10
CALL GEOM(REQXM(IBT),NX)
IDMD(1,3)=IDATE+NX-1
C 204 IF(IY(6).NE.0)GO TO 205
C IDMD(1,4)=2
C GO TO 210
205 NY=15*IBT-9
CALL KGEOM(XNUNT(1,IBT),XNUNT(2,IBT),NY)
IF(NY.GT.NMAX(IBT)) GO TO 205
IF(IDMD(1,1).LT.0.AND.NY.GT.6) GO TO 205
IDMD(1,4)=NY
210 CONTINUE
220 CONTINUE
C WRITE(3,225)IDATA
C 225 FORMAT(9HOPATIENTS,11X,818)
C CROSSMATCH AND RESERVATION SETUP
DO 290 IBT=1,8
290 IDATA(IBT)=0
JPASS=0
IPASS=-1
300 DO 350 I=1,ND
IF(IDMD(1,3).NE.IDATE)GO TO 350
IJK=IDMD(1,1)
IF(IABS(MOD(IJK,2)).NE.JPASS) GO TO 350
IF(IPASS*IJK.LT.0) GO TO 350
NX=IDMD(1,4)
NZ=NX
NY=1
C K=1
IF(IDMD(1,1).GE.0) GO TO 305
C K=0
NY=11-NX
NZ=9-NX
IJK=-IJK
305 IBT=MOD(IJK,10)
IDPAT=IJK
IDATA(IBT)=IDATA(IBT)+NX
C IF(IY(7).NE.0)GO TO 307
C NCF=1
C GO TO 315
307 J=15*IBT-8
CALL RANDU(IY(J),RN)
RN=1.0-RN
DO 310 J=NY,11
IF(XNCF(J,NZ).LT.RN) GO TO 310
NCF=J-NY
GO TO 315
310 CONTINUE

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315 IDCF=0
   IF(NCF.LE.0)GO TO 330
C   IF(IY(8).NE.0)GO TO 316
C   IDCF=1
C   GO TO 317
316 J=15*IBT-7
   CALL RANDU(IY(J),RN)
   IF(XCF(1,IBT).GE.RN) GO TO 317
   IDCF=15*IBT-6
   CALL GEOM(XCF(2,IBT),IDCF)
317 IDCF=IDCF+IDATE
C   IF(IY(10).NE.0)GO TO 319
C   NRET=0
C   GO TO 330
319 J=15*IBT-5
   CALL RANDU(IY(J),RN)
   NZ=NCF
   NY=1
   IF(IDMD(1,1).GE.0) GO TO 318
   NY=11-NCF
   NZ=9-NCF
318 DO 320 J=NY,11
   IF(XNRET(J,NZ ).LT.RN) GO TO 320
   NRET=J-NY
   GO TO 325
320 CONTINUE
325 IF(NRET.LE.0) GO TO 330
C   IF(IY(11).NE.0)GO TO 327
C   IDRET=IDCF
C   GO TO 330
327 IDRET=15*IBT-4
   CALL GEOM(XRET(IBT),IDRET)
   IDRET=IDRET+IDCF-1
330 IF(NX-NCF.LE.0) GO TO 340
C   IF(IY(12).NE.0)GO TO 332
C   IDTOR=IDATE+2
C   GO TO 340
332 IDTOR=15*IBT-3
   CALL KGEOM(XTOR(1,IBT),XTOR(2,IBT),IDTOR)
   IF(IDTOR.LE.0) GO TO 898
   IDTOR=IDTOR+IDATE
340 IAGE=0
   CALL XMATCH(K,890)
350 CONTINUE
   IPASS=-1*IPASS
   IF(IPASS.GT.0) GO TO 300
   JPASS=JPASS+1
   IF(JPASS.LE.1) GO TO 300
C   WRITE(3,355)IDATA
C 355 FORMAT(20HNO. OF RESERVATIONS,8I8)
C   GENERATE REQUISITION (CALL FOR)
   DO 460 IJK=1,8
   IBT=IJK+1
   IF(MOD(IJK,2).EQ.0) IBT=IJK-1
   NOUT(IBT)=0
   CUM(IBT)=0.0

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      XTRN=0.0
      N1=IBEG (IBT)
      N3=N1+N (IBT)
      N2=N3-1
      DO 450 J=N1,N2
      IF (INV(J,7).EQ.IDATE) GO TO 410
      JJ=INV(J,6)
      IF (JJ.GT.0.AND.INV(JJ,7).EQ.IDATE.AND.(JJ.GT.J.OR.JJ.LT.N1))
XGD TO 430
      GO TO 450
410 INV(J,10)=INV(J,10)+1
      NOUT (IBT)=NOUT (IBT)+1
      JJ=INV(J,6)
      IF (JJ.GT.0) INV(JJ,6)=0
      IF (INV(J,8).EQ.0) GO TO 420
C      NON ZERO MEANS UNIT IS TO BE RETURNED
      INV(J,4)=-INV(J,4)
      INV(J,6)=-INV(J,6)
      GO TO 450
420 IR=IDATE-INV(J,2)
      IF (IR.GT.21) IR=21
      CUM (IBT)=CUM (IBT)+IR
      XTRN=XTRN+1.0
      IF (INV(J,3).LE.NUNIT) GO TO 425
C      THIS UNIT HAS BEEN TRANSFUSED
      ITRANS (IBT)=ITRANS (IBT)+1
      IR=IR+1
      XTAB(6,IR,IBT)=XTAB(6,IR,IBT)+1.0
425 INV(J,1)=0
      INV(J,13)=INV(J,13)+IDATE-INV(J,5)
      GO TO 450
C      SECONDARY UNIT OLDER THAN PRIMARY - USE IT
430 DO 440 I=4,8
      IF (I.EQ.6) GO TO 440
      INV(N3,I)=INV(JJ,I)
      INV(JJ,I)=INV(J,I)
      INV(J,I)=INV(N3,I)
440 CONTINUE
      GO TO 410
450 CONTINUE
      IF (XTRN.GT.0.0) CUM (IBT)=CUM (IBT)/XTRN
460 CONTINUE
C      WRITE(3,465)NOUT
C 465 FORMAT(10HOCALL FORS,10X,8I8)
C      WRITE(3,470)(CUM(I),I=1,8)
C 470 FORMAT(20HOAGE AT TRANSFUSION ,8F8.2)
C      EXPIRATION OF LIFE
C      WRITE(3,505)
C 505 FORMAT(43HOEXPIRATION OF LIFE,OUT DATE,CANCEL ,RETURN)
      DO 550 IBT=1,8
      I=0
      K=0
      L=0
      N1=IBEG (IBT)
      N2=N1+N (IBT)-1
      DO 540 J=N1,N2

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      IF(INV(J,2).GT.IDATE-21.OR.INV(J,1).EQ.0) GO TO 540
      IF(INV(J,6).LE.0) GO TO 510
      JJ= INV(J,6)
      INV(JJ,6)=0
      INV(J,6)=0
510  IF(INV(J,4).NE.0) GO TO 520
515  IF(INV(J,3).GT.NUNIT) IOD(1BT)=IOD(1BT)+1
      INV(J,1)=0
      I=I+1
      GO TO 540
520  K=K+1
      IF(INV(J,4).GT.0) GO TO 530
      L=L+1
      K=K-1
      INV(J,11)=INV(J,11)+1
530  INV(J,13)=INV(J,13)+IDATE-INV(J,5)
      GO TO 515
540  CONTINUE
C    WRITE(3,545)1BT,I,K,L
C 545  FORMAT(12X,4I8)
550  CONTINUE
C    PACKING INVENTORY ARRAY
      DO 630 1BT=1,8
      CUM(1BT)=0.0
      N1=1BEG(1BT)
      N2=N1+N(1BT)-1
      NN=N1-1
      DO 620 I= N1,N2
      CUM(1BT)=CUM(1BT)+IDATE-INV(I,2)
      IF(INV(I,1).EQ.0) GO TO 615
      NN=NN+1
      IF(INV(I,6).LE.0) GO TO 605
      II=INV(I,6)
      INV(II,6)=NN
605  DO 610 J=1,13
610  INV(INN,J)=INV(I,J)
      GO TO 620
615  IF(INV(I,3).LE.NUNIT) GO TO 620
      KNT(1BT)=KNT(1BT)+1
      DO 618 IT= 9,13
      IR=INV(I,IT)+1
      IF(IR.GT.22) IR=22
618  XTAB(IT-8,IR,1BT)=XTAB(IT-8,IR,1BT)+1.0
C    1=XM, 2=CF, 3=RET, 4=RES2, 5=TIME ON RES
620  CONTINUE
      CUM(1BT)=CUM(1BT)/N(1BT)
      N(1BT)=NN-N1+1
630  CONTINUE
C    WRITE(3,635)(CUM(I),I=1,8)
C 635  FORMAT(14H0AGE OF AM INV,6X,8F8.2)
C    WRITE(3,640)N
C 640  FORMAT(14H0NEW INVENTORY,6X,8I8)
      CALL INVIN(K,&890)
C    RETURNS OF CALLED FOR BLOOD
      DO 730 1BT=1,8
      IF(N(1BT).GT.0)GO TO 705

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```

      NX=K
      CALL EMERG(K)
      CALL INVIN(K,&890)
705  NOUT(IBT)=0
      IDATA(IBT)=0
      N1=IBEG(IBT)
      N2=N1+N(IBT)-1
      DO 720 J=N1,N2
      IF(INV(J,4).GE.0) GO TO 720
      NOUT(IBT)=NOUT(IBT)+1
      IF(INV(J,8).NE.IDATE.OR.INV(J,7).EQ.0) GO TO 720
      INV(J,13)=INV(J,13)+IDATE-INV(J,5)
      DO 710 I=4,8
710  INV(J,I)=0
      INV(J,11)=INV(J,11)+1
      IDATA(IBT)=IDATA(IBT)+1
720  CONTINUE
      NOUT(IBT)=NOUT(IBT)-IDATA(IBT)
730  CONTINUE
C      WRITE(3,735) IDATA
C 735  FORMAT(8HORETURNS,12X,8I8)
C      WRITE(3,740) NOUT
C 740  FORMAT(17HODUT OF INVENTORY,3X,8I8)
C      WRITE(3,755)(IOD(I),I=1,8)
C 755  FORMAT(16HOCUM. UNITS EXP.,4X,8I8)
      WRITE(3,760)(KNT(I),I=1,8)
760  FORMAT(17HOCUM. UNITS HNDLD,3X,8I8)
      XNP=0.0
      XNPQ=0.0
      DO 765 I=1,8
      XTRN=IOD(I)
      CUM(I)=KNT(I)
      XNP=XNP+XTRN
      XNPQ=XNPQ+CUM(I)
      IF(CUM(I).GT.0.0) CUM(I)=XTRN*100.0/CUM(I)
765  CONTINUE
      CUM(9)=XNP*100.0/XNPQ
      WRITE(3,770)CUM
770  FORMAT(15HOCUM. PCT. EXP.,5X,9F8.2)
C      CANCELLATION OF RESERVATIONS
750  IDATE=IDATE+1
      IF(IDATE.GT.NDAYS) GO TO 900
C      CALL PDUMP(NLM,ICF,3,IBEG(1),N(8),3,NMAX(1),KNT(9),3,
C      XNUNIT,NDAYS,3,NDES,IT,3)
      WRITE(3,40)IDATE
40  FORMAT(13HOTODAY IS DAY,I4)
      DO 850 IBT=1,8
      IABLE(IBT)=0
      IDATA(IBT)=0
      N1=IBEG(IBT)
      N2=N1+N(IBT)-1
      DO 840 J=N1,N2
      IF(INV(J,7).NE.0.OR.INV(J,8).NE.IDATE)GO TO 840
      IDATA(IBT)=IDATA(IBT)+1
      IF(INV(J,6).GT.J.AND.INV(J,6).LE.N2) GO TO 820
      IF(INV(J,6).GT.0.AND.INV(J,6).LT.N1) GO TO 820

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      IF(INV(J,6).GT.0) INV(INV(J,6),6)=0
810 INV(J,13)=INV(J,13)+IDATE-INV(J,5)
      DO 815 I=4,8
815 INV(J,I)=0
      GO TO 840
820 JJ= INV(J,6)
      IF(INV(JJ,7).EQ.0.AND.INV(JJ,8).LE.IDATE)GO TO 810
      INV(JJ,6)=0
      DO 830 I=4,8
      INV(J,I)=INV(JJ,I)
830 INV(JJ,I)=0
      INV(JJ,13)=INV(JJ,13)+IDATE-INV(J,5)
840 CONTINUE
850 CONTINUE
C      WRITE(3,855)IDATA
C 855 FORMAT(18HNOTAKEN OFF RESERVE,2X,818)
C      DEMAND ARRAY CONSOLIDATION
      NN=0
      IF(ND.EQ.0) GO TO 100
      DO 880 I=1,ND
      IF(IDMD(I,3).LT.IDATE) GO TO 880
      NN=NN+1
      DO 870 J=1,4
870 IDMD(NN,J)=IDMD(I,J)
880 CONTINUE
      ND=NN
      GO TO 100
C      ERROR IN INVENTORY STORAGE
889 K=1BT
890 WRITE(3,895) K,IDATE
895 FORMAT(10H0INV. TYPE,12,26H OVERFLOWED STORAGE ON DAY,13)
898 CALL PDUMP(NLM,ICF,3,IV(1,1),IREQ(9),3,NMAX(1),IDES(8),3,
      XNUNIT,NDAYS,3,NDES,IT,3,XTOR(1,1),XRET(8),5)
900 NDAYS=IDATE-22
C      OUTPUT AT END OF SIMULATION
      CALL OUTPUT
      STOP
      END
      SUBROUTINE BEGIN
      IMPLICIT INTEGER*2 (I-N)
      INTEGER IY,IDATA,IJK
      DIMENSION IY(120)
      COMMON IY,NLM,IAGE,IDATE,IUNIT,IBT,N1,N2,I1,IDPAT,NX,NCF,IDCF,NRET
      X,IDRET,IDTOR,ICF,YNRET,YNCF
      COMMON IV(125,3),IBEG(9),N(8),INV(500,13),IREQ(9)
      COMMON/A/ XTAB(6,25,8),CUM(9),XTOR(2,8),
      1XORDAG(22,8),XNDNR(8),XNPAT(2,8),REQXM(8),XNUNT(2,8),XNCF(11,10),
      2XCF(2,8),XNRET(11,10),XRET(8),NMAX(8),IOD(9),ITRANS(9),KNT(9),
      3IDMD(200,4),NOUT(8),IDES(8)
      DIMENSION XINVN(2,8),XINVAG(22,8),RSVPB(8),
      1 PAGE(8),HEAD(16),BTYPE(9)
      2,SUBHED(16),COLHD1(16),COLHD2(16),TABHED(16,7),IDATA(8)
      EQUIVALENCE (XINVAG(1,1),XORDAG(1,1)),(XINVN(1,1),XNPAT(1,1)),
      1(REQXM(1),RSVPB(1)),(IDATA(1),CUM(1)),(PAGE(1),XNDNR(1)),(HEAD(1),
      2XINVN(1,1)),(SUBHED(1),XTOR(1,1)),(BTYPE(1),XNCF(1,1)),(COLHD1(1),
      3XNUNT(1,1)),(COLHD2(1),XCF(1,1)),(TABHED(1,1),XORDAG(1,1))

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COMMON/B/ NUNIT,ND,NDPAT,NDAYS,IJK
COMMON/C/ NOLD,NAGE,NDBLA,NDBLN,NDBLP
READ(1,1)IY(1),NDAYS,NUNIT,NOLD,NAGE,NDBLA,NDBLN,NDBLP
READ(1,1)(IY(I),I=1,15)
DO 7 I=1,7
IK= 15*I
DO 7 J=1,15
IJ=IK+J
II=I+J
IF(II.GT.12)II=II-12
IY(IJ)=IY(II)
7 CONTINUE
1 FORMAT(16I5)
READ(1,1)IBEG
READ(1,3)XINVN
3 FORMAT(16F5.4)
READ(1,3)XTOR
READ(1,3)RSVPB
READ(1,5)XINVAG
5 FORMAT(11F5.4)
C INITIATIZATION AND STARTING INVENTORY POSITION
IUNIT=0
IDATE=21
DO 2 I=1,8
KNT(I)=0
N(I)=0
NOUT(I)=0
IREQ(I)=0
ITRANS(I)=0
IOD(I)=0
DO 2 J=1,6
DO 2 K=1,25
XTAB(J,K,I)=0.0
2 CONTINUE
DO 4 I=1,500
DO 4 J=1,13
4 INV(I,J)=0
C DOBI=2,12
C 8 IY(I)=IY(1)
DO 30 II =1,8
NLM=XINVN(1,II)+0.5
IF(NLM.LE.0) GO TO 30
DO 15 J=1,NLM
IUNIT=IUNIT+1
IV (J,1)=IUNIT
CALL RANDU(IY(15),RN)
DO 10 K=1,22
IF(XINVAG(K,II).LT.RN)GO TO 10
IV (J,2)=23-K
GO TO 15
10 CONTINUE
15 IV (J,3)=II
CALL INVIN(I,&25)
25 N1=IBEG(II)
XNP=N(II)*RSVPB(II)
XNPQ=XNP*(1.0-RSVPB(II))

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      NX=13
      CALL BIN(XNP,XNPQ,NX)
      N2=N1+NX
      DO 20 J=N1,N2
        INV(J,4)=11
        INV(J,5)=21
        IF(INV(J,2).GT.2) GO TO 27
        INV(J,7)=22
        GO TO 20
27  ITOR=14
      CALL KGEOM(XTOR(1,II ),XTOR(2,II ),ITOR)
      INV(J,8)=21+ITOR
20  CONTINUE
30  CONTINUE
      WRITE(3,35) N
35  FORMAT(12H1 INITIAL INV,8X,8I8)
      NDPAT=0
      READ(1,1)IDES
      READ(1,5)XORDAG
      READ(1,3)XNDNR
      READ(1,3)XNPAT
      READ(1,3)REQXM
      READ(1,3)XNUNT
      READ(1,3)XCF
      READ(1,3)XRET
      READ(1,1)NMAX
      READ(1,5)XNCF,XNRET
      RETURN
      END
      SUBROUTINE XMATCH(K,*)
      IMPLICIT INTEGER*2 (1-N)
      INTEGER IY,IJK
      DIMENSION IY(120)
      COMMON IY,NLM,IAGE,IDATE,IUNIT,IBT,N1,N2,I1,IDPAT,NX,NCF,IDCF,NRET
X, IDRET, IDTOR, ICF, XNRET, XNCF
      COMMON IV(125,3),IBEG(9),N(8),INV(500,13),IREQ(9)
      COMMON/C/ NOLD,NAGE,NOBLA,NDBLN,NOBLP
      COMMON/D/ IABLE(8)
      ICF=0
      XNRET=NRET
      XNCF=NCF
      IREQ(1BT)=IREQ(1BT)+NX
      IJK=1BT
      IF(MOD(IJK,2).EQ.0) GO TO 15
      IF(IABLE(1BT+1).EQ.1) GO TO 15
      IAGE=1BT+1
      I1=IBEG(IAGE)
      N2=I1+N(IAGE)-1
      GO TO 20
15  I1=IBEG(1BT)
      N2=I1+N(1BT)-1
20  N1=I1
      DO 40 I=1,NX
        5 CALL RESRV(J,&30)
        8 IF(IAGE.EQ.0) GO TO 25
        IABLE(IAGE)=1

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    IAGE=0
    NX=NX-1+1
    GO TO 15
25 IF(NLM.EQ.0) CALL EMERG(1)
    WRITE(3,10)
10 FORMAT(31H0INVENTORY MADE AVAILABLE EARLY)
    J=IBT
    CALL INVIN(K,&50)
    IBT=J
    N2=I1+N(IBT)-1
    N1=I1
    GO TO 5
50 RETURN 1
30 N1=I1
40 CONTINUE
    RETURN
    END
C   SUBROUTINE XMATCH(K,*)
    DOUBLE CROSSMATCH ROUTINE- NO SAME DAY REQUIREMENT
    IMPLICIT INTEGER*2 (I-N)
    INTEGER IY,IJK
    DIMENSION IY(120)
    COMMON IY,NLM,IAGE,IDATE,IUNIT,IBT,N1,N2,I1,IDPAT,NX,NCF,IDCF,NRET
X, IDRET, IDTOR, ICF, XNRET, XNCF
    COMMON IV(125,3), IBEG(9), N(8), INV(500,13), IREQ(9)
    COMMON/C/ NOLD,NAGE,NDBLA,NDBLN,NDBLP
    COMMON/D/ IABLE(8)
    ICF=0
    XNRET=NRET
    XNCF=NCF
    IREQ(IBT)=IREQ(IBT)+NX
    IJK=IBT
    NSAV=NAGE
    IF(MOD(IJK,2).EQ.0) GO TO 2
    IF(IABLE(IBT+1).EQ.1) GO TO 2
    IAGE=IBT+1
    I1=IBEG(IAGE)
    N2=I1+N(IAGE)-1
    GO TO 3
2   I1=IBEG(IBT)
    N2=I1+N(IBT)-1
3   DO 60 L=1,NX
5   N1=I1
    DO 10 I=N1,N2
    IF(IAGE.GT.0.AND.IDATE-INV(I,2).LT.NAGE) GO TO 12
    IF(IDATE-INV(I,2).LT.NDBLA)GO TO 11
C   IF(IDATE-INV(I,2).LT.NDBLA)GO TO 9
C   IF(K.EQ.0) GO TO 10
    IF(I-N1.GE.NDBLN)GO TO 11
    IF(100*(I-N1)/(N2-N1+1).GE.NDBLP)GO TO 11
    IF(INV(I,6).NE.0.OR.INV(I,4).EQ.IDPAT.OR.INV(I,4).LE.0) GOTO10
    IF(IDC.F.GT.INV(I,2)+21)GO TO 10
    ISAV=I
C   N1=N(IBT)/3+IBEG(IBT)
C   N1=N(IBT)/2+IBEG(IBT)
C   N1=N(IBT)/5+IBEG(IBT)

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      N1=N(1BT)/NOLD+1BEG(1BT)
C     ABOVE STATEMENT GETS 50PCT NEW-LEAVE OUT FOR ALL OLD
      IF(1AGE.NE.0) GO TO 7
      IF(1SAV.GT.N1) GO TO 15
      GO TO 20
7     1JK=INV(1,4)
      IF(MOD(1JK,2).EQ.0) GO TO 8
      11=1BEG(1BT)
      N2=11+N(1BT)-1
      1AGE=0
      GO TO 20
8     NAGE=0
      N1=11
      N2=11+N(1AGE)-1
      GO TO 20
12    1ABLE(1AGE)=-1
      GO TO 11
C     9     N1=1
C           1SAV=0
C           GO TO 20
10    CONTINUE
11    1SAV=0
15    N1=11
20    CALL RESRV(J,&30)
      NAGE=NSAV
      IF(1AGE.NE.0) GO TO 35
      IF(N1.GT.11) GO TO 15
      IF(NLM.EQ.0) CALL EMERG(L)
      WRITE(3,25)
25    FORMAT(31H0INVENTORY MADE AVAILABLE EARLY)
      J=1BT
      CALL INVIN(K,&50)
      1BT=J
      N2=11+N(1BT)-1
      GO TO 15
35    1SAV=0
      1AGE=0
      1ABLE(1BT)=-1
      11=1BEG(1BT)
      N2=11+N(1BT)-1
      GO TO 5
50    RETURN 1
30    NAGE=NSAV
      IF(1SAV.EQ.0) GO TO 60
      INV(J,6)=1SAV
      INV(1SAV,12)=INV(1SAV,12)+1
      INV(1SAV,6)=J
60    CONTINUE
      IF(1ABLE(1BT)+1ABLE(1BT+1).EQ.-2) 1ABLE(1BT+1)=1
      RETURN
      END
      SUBROUTINE EMERG(K)
      IMPLICIT INTEGER*2 (1-N)
      INTEGER IY
      DIMENSION IY(120)
      COMMON IY,NLM,1AGE,1DATE,1UNIT,1BT,N1,N2,11,1DPAT,NX,NCF,1DCF,NRET

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X, IDRET, IDTOR, ICF, YNRET, YNCF
COMMON IV(125,3), IBEG(9), N(8), INV(500,13), IREQ(9)
COMMON/A/ XTAB(6,25,8), CUM(9), XTOR(2,8),
1XORDAG(22,8), XNDNR(8), XNPAT(2,8), REQXM(8), XNUNT(2,8), XNCF(11,10),
2XCF(2,8), XNRET(11,10), XRET(8), NMAX(8), IOD(9), ITRANS(9), KNT(9),
3IDMD(200,4), NOUT(8), IDES(8)
NLM=NX-K+1
WRITE(3,15)NLM,IBT
15 FORMAT(19HOSPECIAL ORDER FOR ,12,21H UNITS OF BLOOD TYPE,12)
I=15*IBT-14
CALL RANDU(IY(1),RN)
DO 110 I=1,22
IF(RN.GE.XORDAG(I,IBT)) GO TO 110
IAGO=IDATE+1-I
GO TO 115
110 CONTINUE
115 DO 20 J=1,NLM
IUNIT=IUNIT+1
IV(J,1)=IUNIT
IV(J,2)=IAGO
IV(J,3)=IBT
20 CONTINUE
RETURN
END
SUBROUTINE RESRV(J,*)
IMPLICIT INTEGER*2 (I-N)
INTEGER IY
DIMENSION IY(120)
COMMON IY,NLM,IAGE,IDATE,IUNIT,IBT,N1,N2,I1,IDPAT,NX,NCF,IDCF,NRET
X,IDRET,IDTOR,ICF,XNRET,XNCF
COMMON IV(125,3),IBEG(9),N(8),INV(500,13),IREQ(9)
COMMON/C/ NOLD,NAGE,NDBLA,NDBLN,NDBLP
DO 20 J=N1,N2
IF(INV(J,4).NE.0)GO TO 20
IF(IDCF.GT.INV(J,2)+21) GO TO 20
IF(IAGE.EQ.0) GO TO 5
IF(IDATE-INV(J,2).LT.NAGE) GO TO 30
5 INV(J,4)=IDPAT
INV(J,5)=IDATE
INV(J,9)=INV(J,9)+1
IF(ICF.GE.NCF) GO TO 10
ICF=ICF+1
INV(J,7)=IDCF
INV(J,8)=0
TEST=XNRET/XNCF
XNCF=XNCF-1.0
CALL RANDU(IY(15),RN)
IF(RN.GT.TEST) RETURN1
INV(J,8)=IDRET
XNRET=XNRET-1.0
RETURN 1
10 INV(J,7)=0
INV(J,8)=IDTOR
RETURN 1
20 CONTINUE
30 RETURN

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END
SUBROUTINE OUTPUT
IMPLICIT INTEGER*2 (I-N)
INTEGER IY, IDATA, IJK
DIMENSION IY(120)
COMMON IY, NLM, IAGE, IDATE, IUNIT, IBT, N1, N2, I1, IDPAT, NX, NCF, IDCF, NRET
X, IDRET, IDTOR, ICF, YNRET, YNCF
COMMON IV(125,3), IBEG(9), N(8), INV(500,13), IREQ(9)
COMMON/A/ XTAB(6,25,8), CUM(9), XTOR(2,8),
1XORDAG(22,8), XNDNR(8), XNPAT(2,8), REQXM(8), XNUNT(2,8), XNCF(11,10),
2XCF(2,8), XNRET(11,10), XRET(8), NMAX(8), IOD(9), ITRANS(9), KNT(9),
3IDMD(200,4), NOUT(8), IDES(8)
DIMENSION XINVN(2,8), XINVAG(22,8), RSVPB(8),
1PAGE(8), HEAD(16), BTYPE(9)
2, SUBHED(16), COLHD1(16), COLHD2(16), TABHED(16,7), IDATA(8)
EQUIVALENCE (XINVAG(1,1), XORDAG(1,1)), (XINVN(1,1), XNPAT(1,1)),
1(REQXM(1), RSVPB(1)), (IDATA(1), CUM(1)), (PAGE(1), XNDNR(1)), (HEAD(1),
2XINVN(1,1)), (SUBHED(1), XTOR(1,1)), (BTYPE(1), XNCF(1,1)), (COLHD1(1),
3XNUNT(1,1)), (COLHD2(1), XCF(1,1)), (TABHED(1,1), XORDAG(1,1))
COMMON/B/ NUNIT, ND, NDPAT, NDAYS, IJK
KNT(9)=0
IOD(9)=0
ITRANS(9)=0
IREQ(9)=0
DO 902 IBT=1,8
KNT(9)=KNT(9)+KNT(IBT)
IOD(9)=IOD(9)+IOD(IBT)
ITRANS(9)=ITRANS(9)+ITRANS(IBT)
IREQ(9)=IREQ(9)+IREQ(IBT)
XJK=IOD(IBT)
YJK=KNT(IBT)
902 CUM(1BT)=100.*XJK/YJK
XJK=IOD(9)
YJK=KNT(9)
CUM(9)=100.*XJK/YJK
READ(1,905)PAGE
905 FORMAT(16A4)
READ(1,905)HEAD, SUBHED, COLHD1, COLHD2, TABHED
READ(1,905)BTYPE
WRITE(3,910)PAGE
910 FORMAT(1H1,40X,8A4///)
WRITE(3,915) HEAD, SUBHED
915 FORMAT(1H0,25X,16A4/1H0,25X,16A4//)
WRITE(3,915)(TABHED(1,7),I=1,16)
WRITE(3,920)BTYPE
920 FORMAT(1H0,40X,9(3X,A4,3X))
WRITE(3,925)IREQ
925 FORMAT(26HONO. OF REQUESTS PROCESSED,14X,9(2X,I6,2X))
WRITE(3,930)KNT
930 FORMAT(30HONO. OF UNITS OF BLOOD HANDLED,10X,9(2X,I6,2X))
WRITE(3,935)ITRANS
935 FORMAT(24HONO. OF UNITS TRANSFUSED,16X,9(2X,I6,2X))
WRITE(3,940)IOD
940 FORMAT(25HONO. OF UNITS OUT OF DATE,15X,9(2X,I6,2X))
WRITE(3,945) CUM
945 FORMAT(32HOPERCENT OF BLOOD NOT TRANSFUSED,8X,9(2X,F6.2,2X))

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DO 990 I=1,6
WRITE(3,910)PAGE
WRITE(3,915)HEAD,SUBHED
WRITE(3,915)(TABHED(J,I),J=1,16)
WRITE(3,950)COLHD1(2*I-1),COLHD1(2*I),(BTYPE(J),J=1,8)
950 FORMAT(1H0,2A4,2X,8(5X,A4,6X))
WRITE(3,955)COLHD2
955 FORMAT(1H0,10X,8(2X,A4,3X,A4,2X)//)
DO 965 IBT=1,8
CUM(IBT)=0.0
DO 960 IR=1,22
XR=IR-1
XFF=XTAB(I,IR,IBT)
XTAB(I,23,IBT)=XTAB(I,23,IBT)+XR*XFF
XTAB(I,24,IBT)=XTAB(I,24,IBT)+(XR**2)*XFF
XTAB(I,25,IBT)=XTAB(I,25,IBT)+XFF
960 CONTINUE
IF(XTAB(I,25,IBT).LE.0.0) GO TO 965
XTAB(I,23,IBT)=XTAB(I,23,IBT)/XTAB(I,25,IBT)
XTAB(I,24,IBT)=XTAB(I,24,IBT)/XTAB(I,25,IBT)-XTAB(I,23,IBT)**2
965 CONTINUE
DO 980 IR=1,22
JR=IR-1
DO 970 IBT=1,8
IF(XTAB(I,25,IBT).LE.0)GO TO 970
XTAB(I,IR,IBT)=XTAB(I,IR,IBT)*100.0/XTAB(I,25,IBT)
CUM(IBT)=CUM(IBT)+XTAB(I,IR,IBT)
970 CONTINUE
WRITE(3,975)JR,(XTAB(I,IR,IBT),CUM(IBT),IBT=1,8)
975 FORMAT(4X,12,5X,8(F8.2,F7.2))
980 CONTINUE
WRITE(3,982)(XTAB(I,23,IBT),IBT=1,8)
982 FORMAT(11HOAVERAGE ,8F15.4)
WRITE(3,984)(XTAB(I,24,IBT),IBT=1,8)
984 FORMAT(11HOVARIANCE ,8F15.4)
DO 985 IBT=1,8
IF(XTAB(I,24,IBT).GT.0.0)XTAB(I,24,IBT)=XTAB(I,24,IBT)**0.5
985 CONTINUE
WRITE(3,986)(XTAB(I,24,IBT),IBT=1,8)
986 FORMAT(11HOSTD. DEV. ,8F15.4)
WRITE(3,988)(XTAB(I,25,IBT),IBT=1,8)
988 FORMAT(11HONO. OF OBS,8F15.0)
990 CONTINUE
RETURN
END
SUBROUTINE INVIN(I,*)
IMPLICIT INTEGER*2 (I-N)
INTEGER IY
DIMENSION IY(120)
COMMON IY,NLM,IAGE,IDATE,IUNIT,IBT,N1,N2,I1,IOPAT,NX,NCF,IOCF,NRE
X,IDRET,IDTOR,ICF,XNRET,XNCF
COMMON IV(125,3),IBEG(9),N(8),INV(500,13),IREQ(9)
IF(NLM.LE.0) RETURN
DO 40 J=1,NLM
IBT=IV(J,3)
N1=IBEG(IBT)

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      N2=N1+N(1BT)
      INV(N2,2)=IDATE+1
      DO 30 I=N1,N2
      IF(IV(J,2).GE.INV(I,2)) GO TO 30
      DO 20 1J=1,N2
      IK=N2+I-1J
      DO 10 1L=1,13
      INV(IK+1,1L)=INV(IK,1L)
10    INV(IK,1L)=0
      IF(INV(IK+1,6).LE.0) GO TO 20
      II=INV(IK+1,6)
      INV(II,6)=IK+1
20    CONTINUE
      INV(I,1)=IV(J,1)
      INV(I,2)=IV(J,2)
      INV(I,3)=IDATE
      N(1BT)=N(1BT)+1
      GO TO 40
30    CONTINUE
40    CONTINUE
      NLM=0
      DO 50 I=1,8
      IF(1BEG(I)+N(I).GE.1BEG(I+1))RETURN
50    CONTINUE
      RETURN
      END
      SUBROUTINE BIN(XP,XQ,NX)
      IMPLICIT INTEGER*2 (1-N)
      INTEGER IY
      DIMENSION IY(120)
      COMMON IY
      K=NX
      NX=0
      P=1-(XQ/XP)
      IF(P)7,7,8
8     N=XP/P
      DO 5 I=1,N
      CALL RANDU(IY(K),RN)
      IF(RN-P)9,9,5
9     NX=NX+1
5     CONTINUE
7     RETURN
      END
      SUBROUTINE KGEOM(XK,XMU,NX)
      IMPLICIT INTEGER*2 (1-N)
      INTEGER IY
      DIMENSION IY(120)
      COMMON IY
      K=NX
      NX=2
      CALL RANDU(IY(K),RN)
      IF(RN.LT.XK) RETURN
      XMM=1.0/XMU
      NX=K
      CALL GEOM(XMM,NX)
      RETURN

```

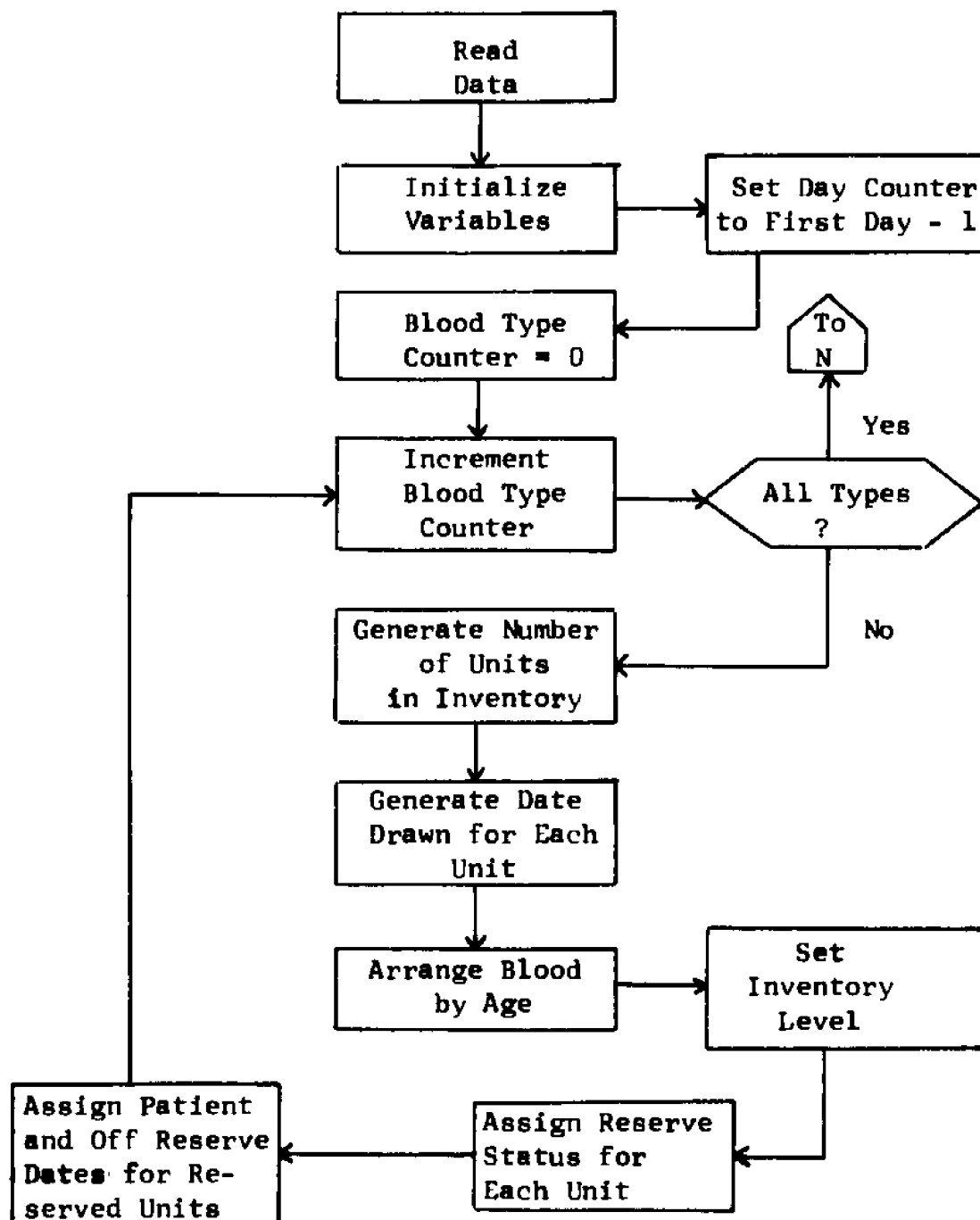
```

END
SUBROUTINE POIS(P,NX)
  IMPLICIT INTEGER*2 (I-N)
  INTEGER IY
  DIMENSION IY(120)
  COMMON IY
  K=NX
  NX=0
  B=EXP(-P)
  TR=1.0
5  CALL RANDU(IY(K),RN)
  TR=TR*RN
  IF(TR-B)10,8,8
8  NX=NX+1
  GO TO 5
10 RETURN
END
SUBROUTINE GEOM(Q,NX)
  IMPLICIT INTEGER*2 (I-N)
  INTEGER IY
  DIMENSION IY(120)
  COMMON IY
  K=NX
  NX=0
  P=1.0-(1.0/Q)
  IF(P.LE.0) GO TO 20
  QR=ALOG(P)
10 CALL RANDU(IY(K),RN)
  RN=1.0-RN
  IF(RN.LE.0) GO TO 10
  NX=ALOG(RN)/QR+1.0
20 RETURN
END
SUBROUTINE RANDU(IX,YFL)
  IX=IX*65539
  IF(IX)5,6,6
5  IX=IX+2147483647+1
6  YFL=IX
  YFL=YFL*.4656613E-9
  RETURN
END

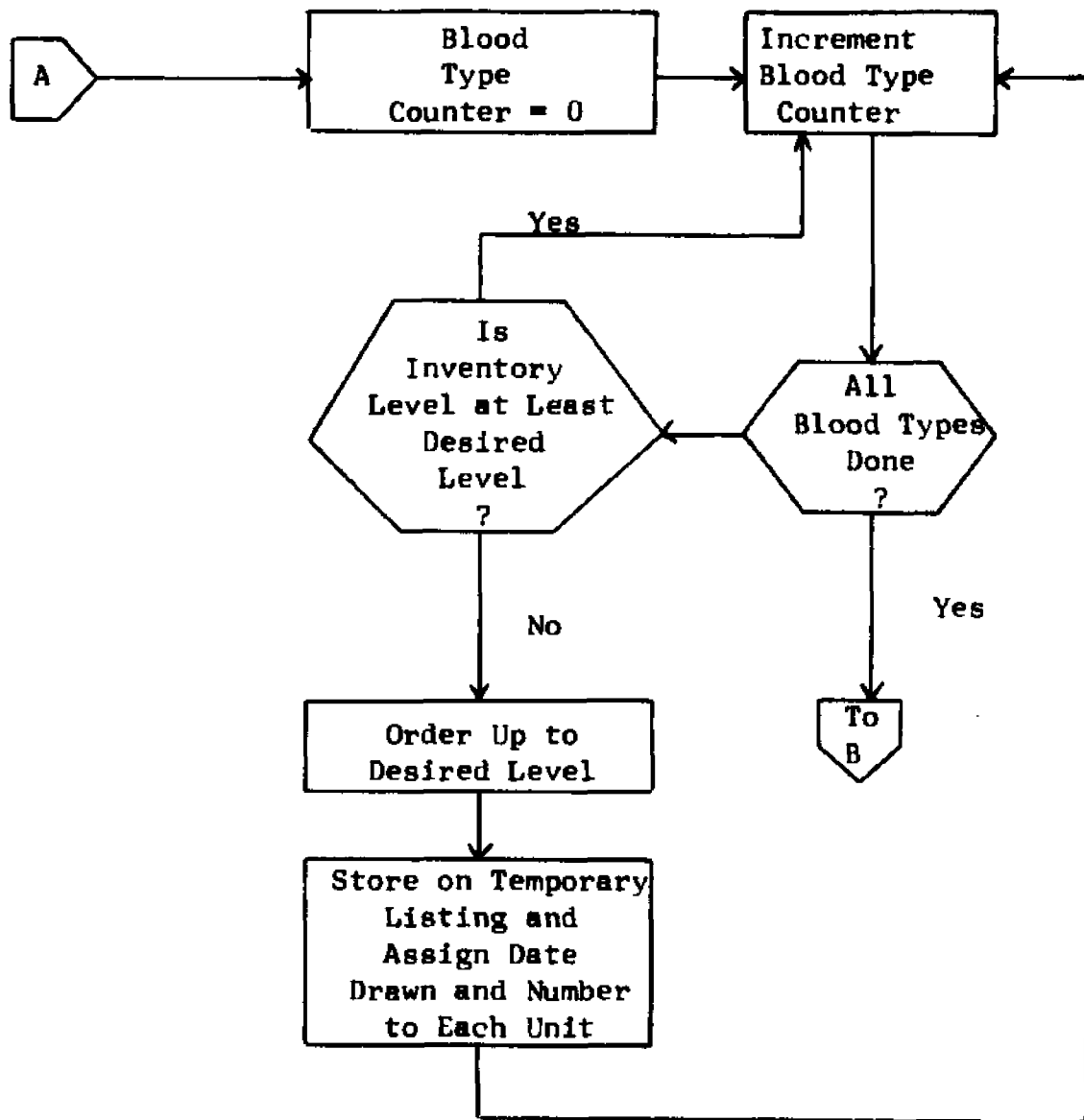
```

APPENDIX V**FLOW DIAGRAM OF THE HOSPITAL BLOOD
BANK INVENTORY SIMULATOR**

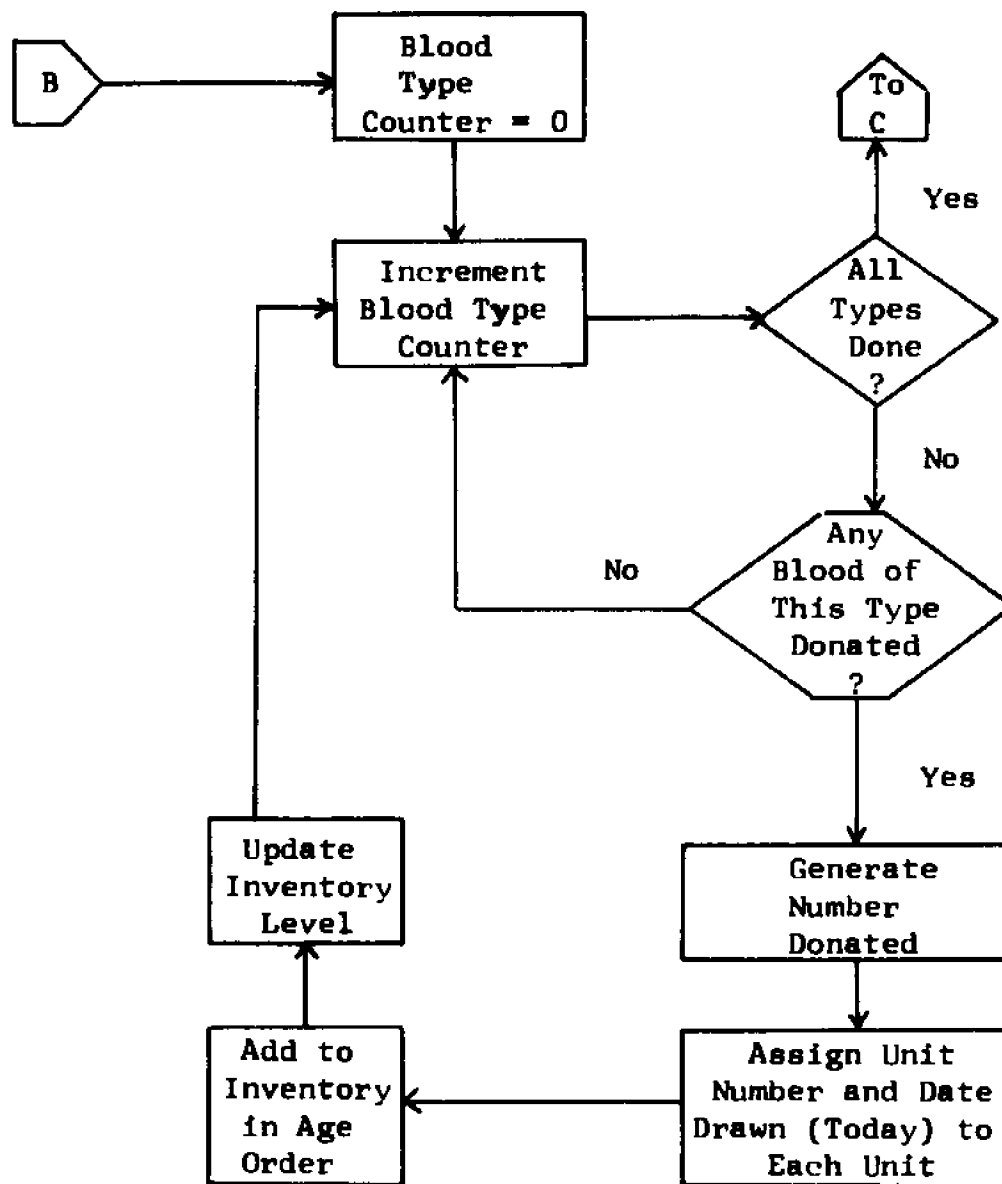
INVENTORY INITIALIZATION
(SUBROUTINE BEGIN)



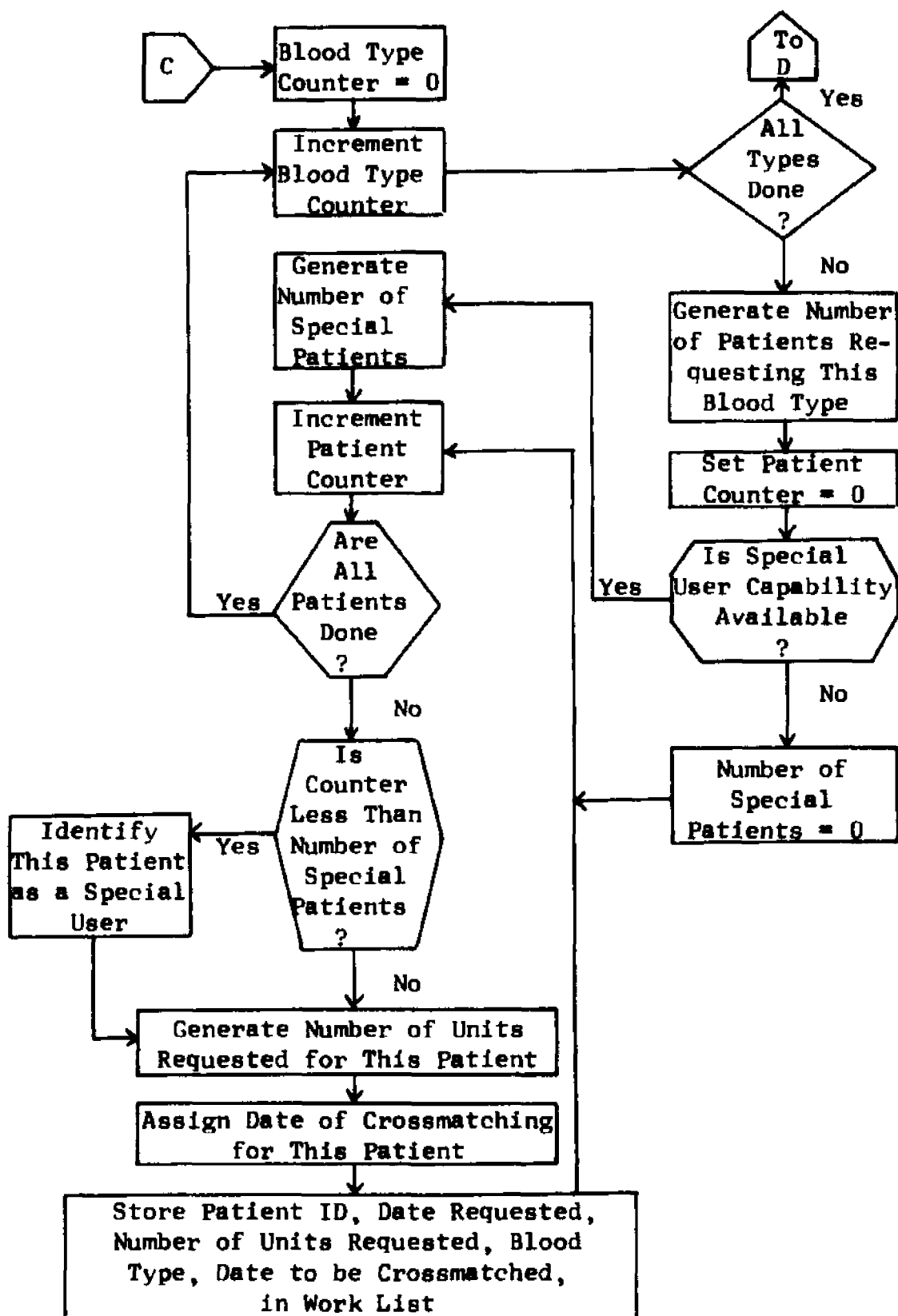
ORDERING OF BLOOD



RECEIPT OF DONATIONS

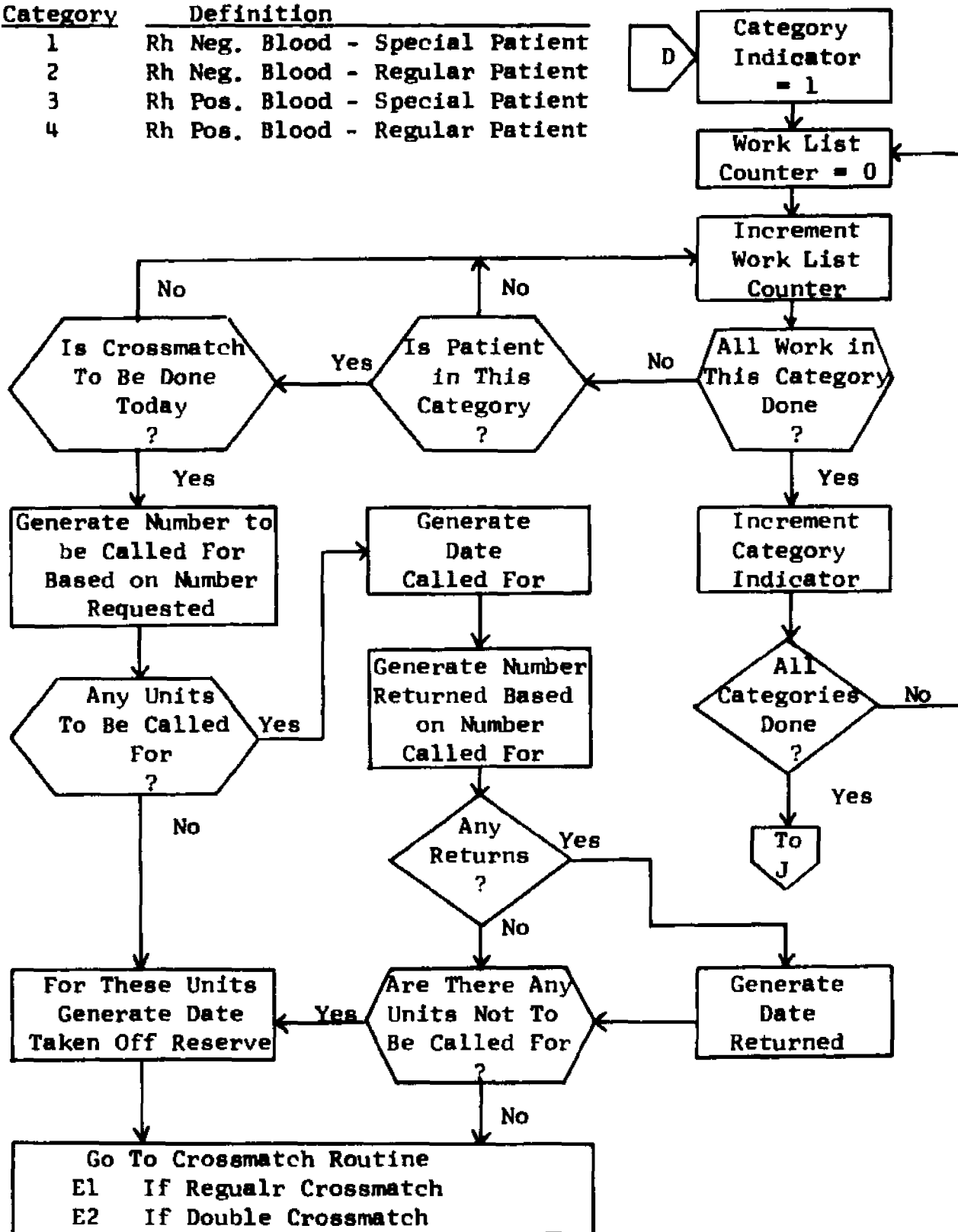


GENERATION OF REQUEST SLIPS

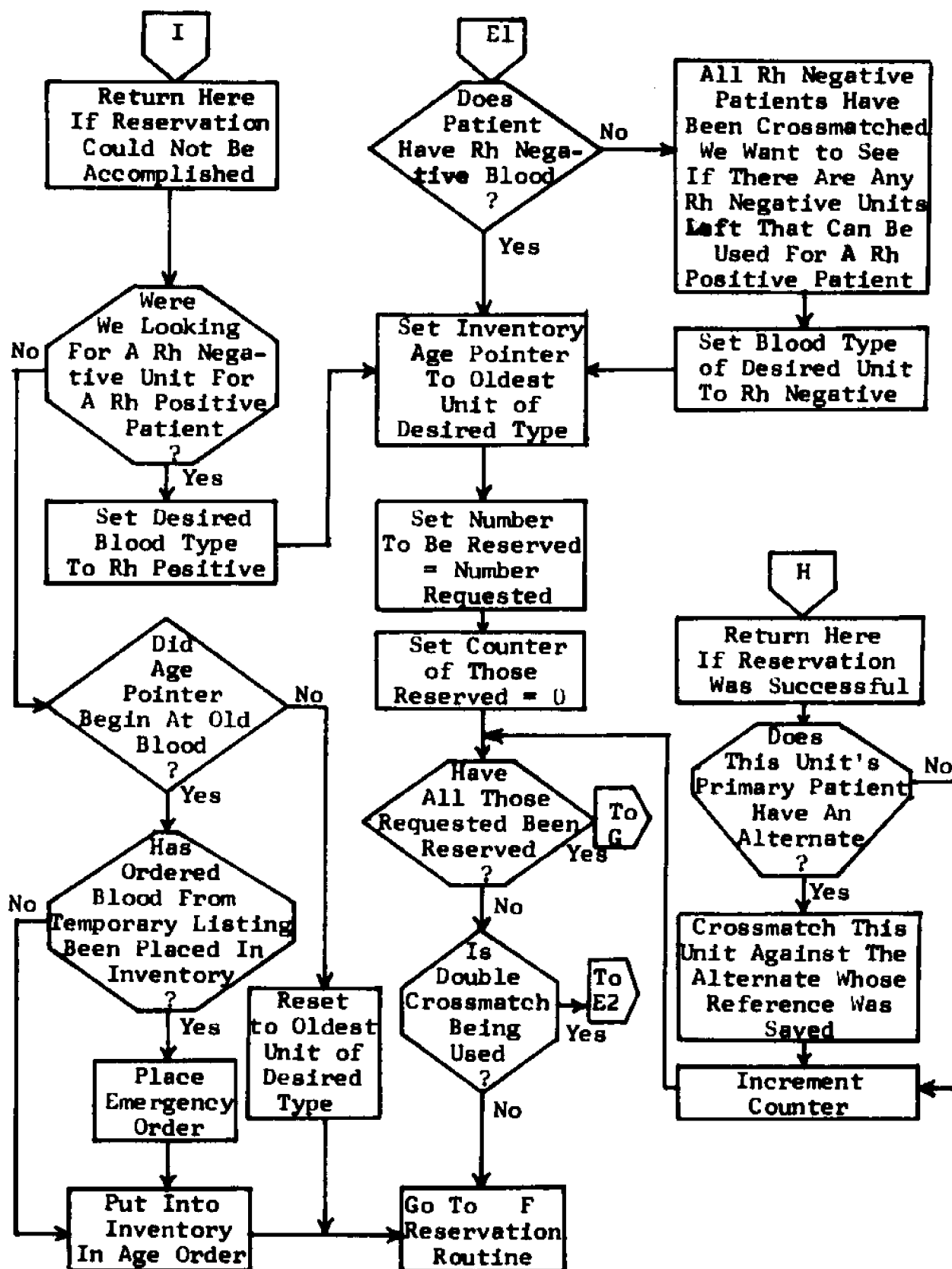


CROSSMATCH AND RESERVATION SETUP

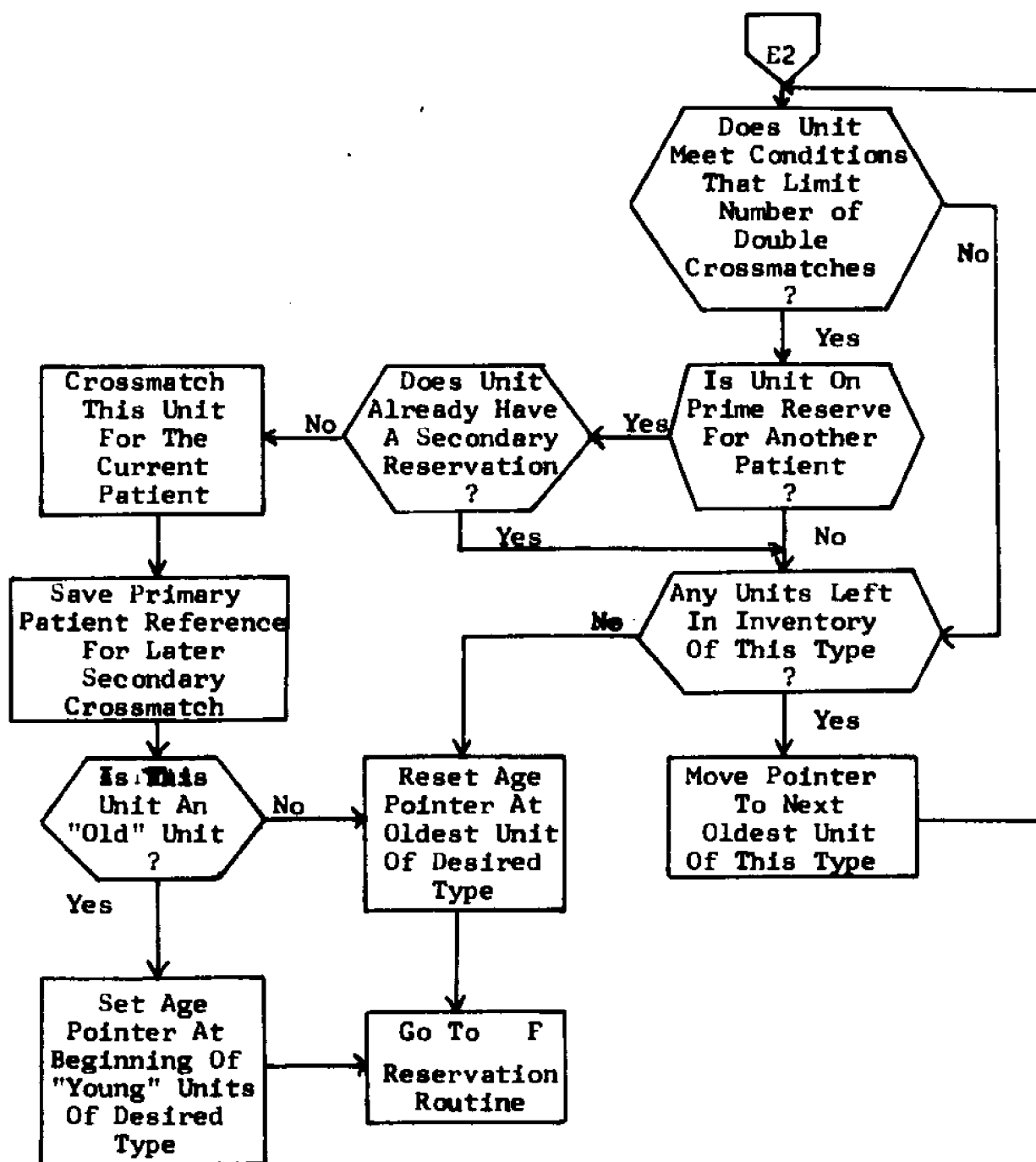
Category	Definition
1	Rh Neg. Blood - Special Patient
2	Rh Neg. Blood - Regular Patient
3	Rh Pos. Blood - Special Patient
4	Rh Pos. Blood - Regular Patient



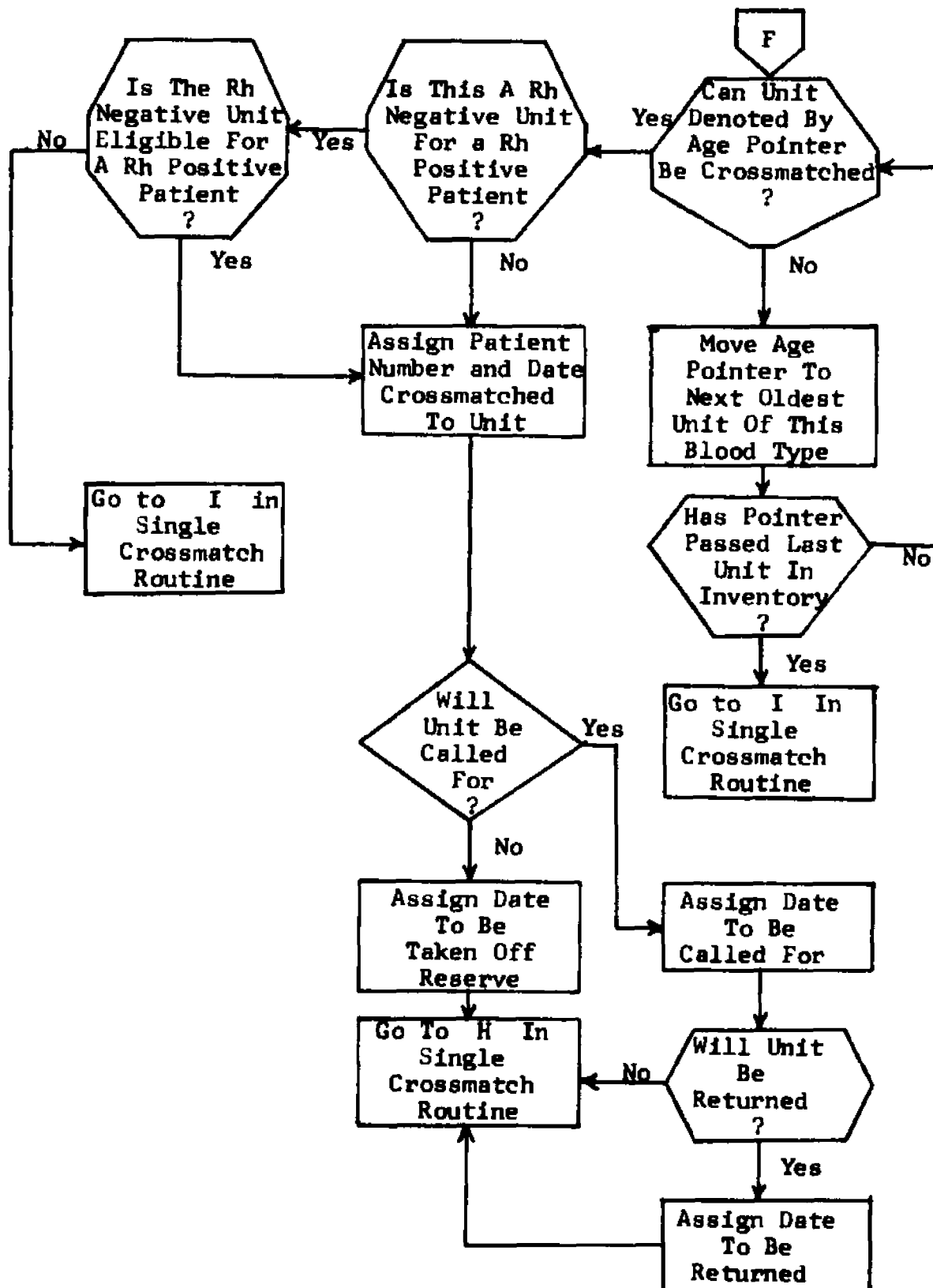
SINGLE CROSSMATCH ROUTINE



DOUBLE CROSSMATCH ROUTINE

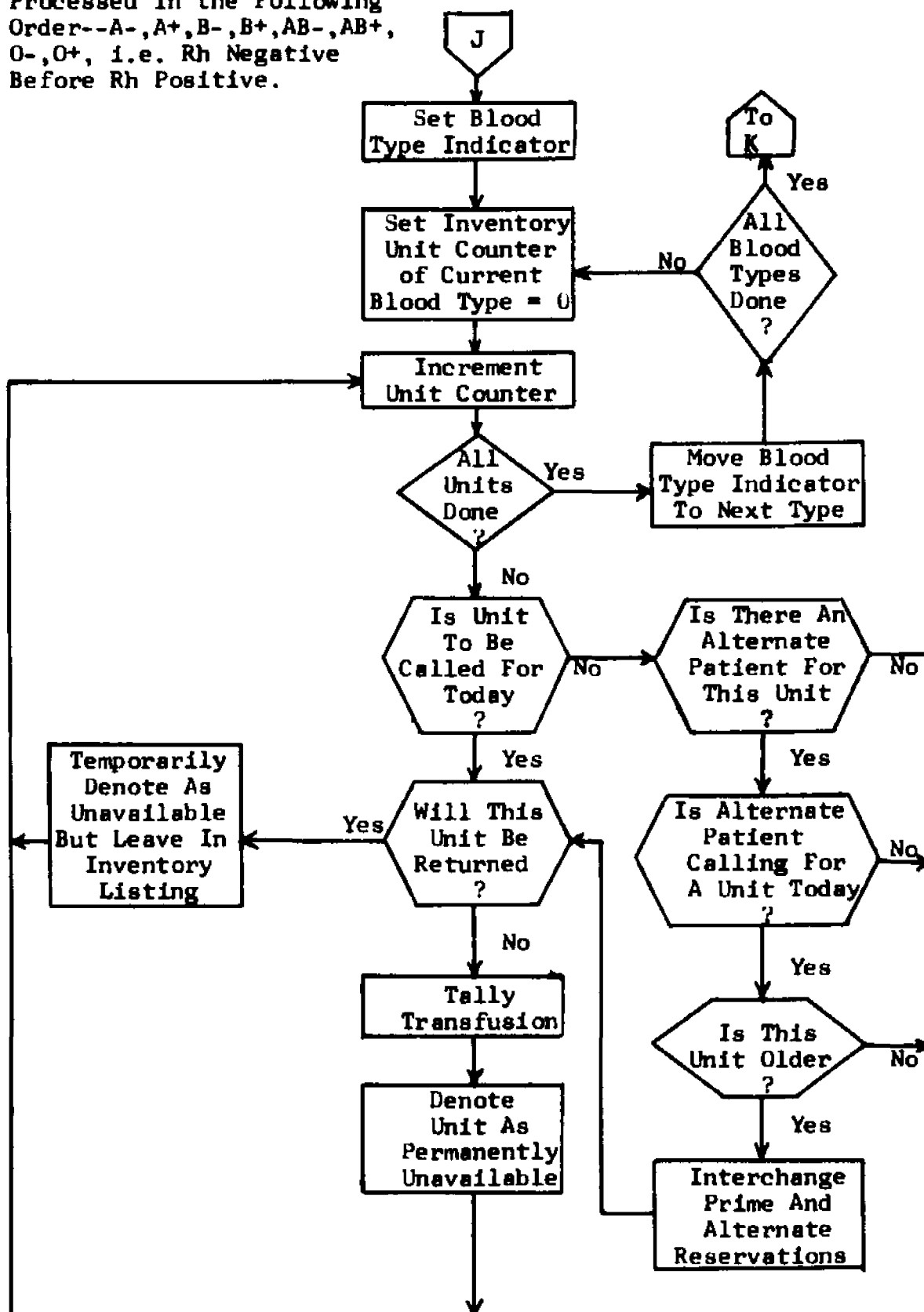


RESERVATION ROUTINE

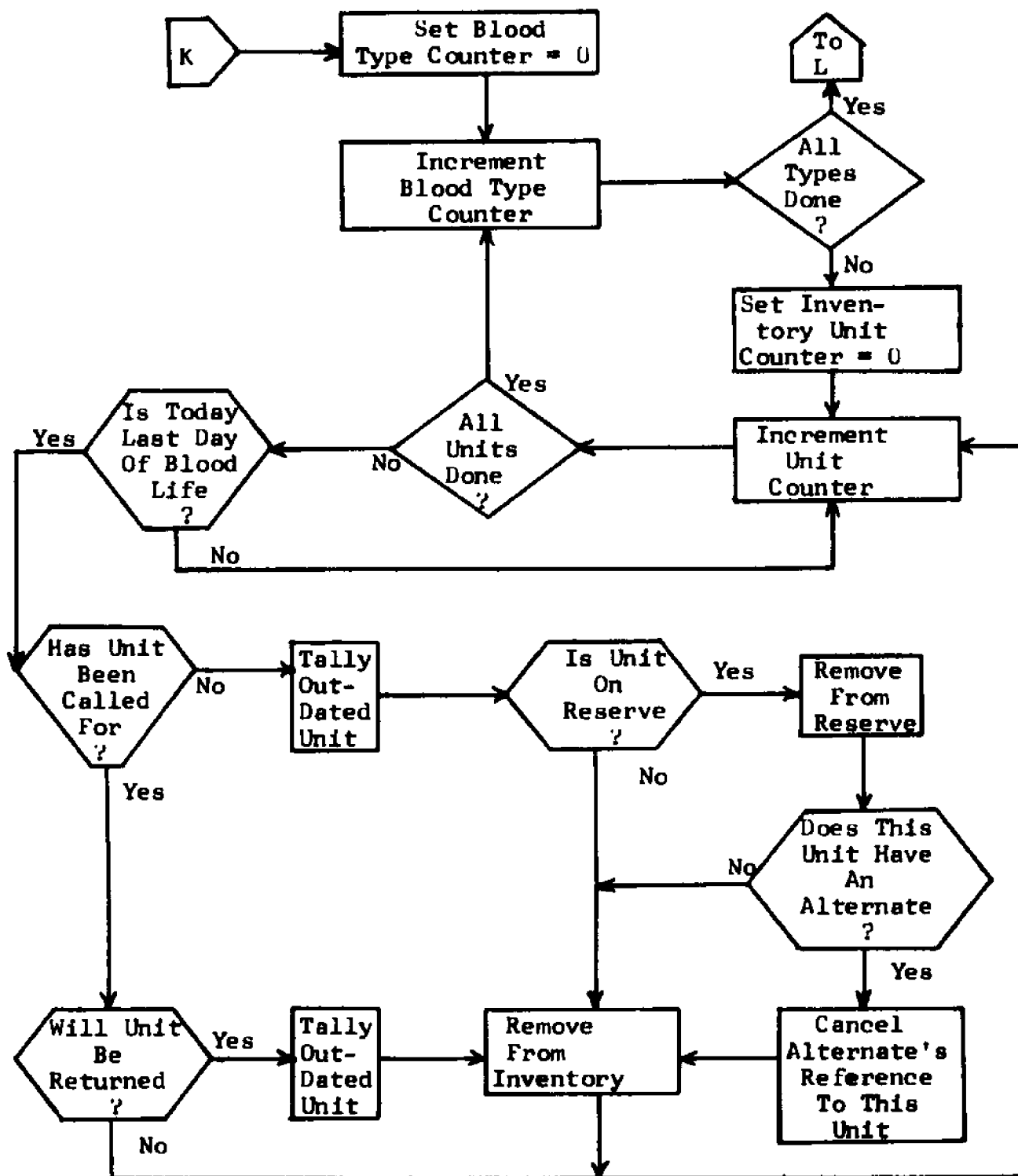


GENERATION OF REQUISITIONS (CALL FORS)

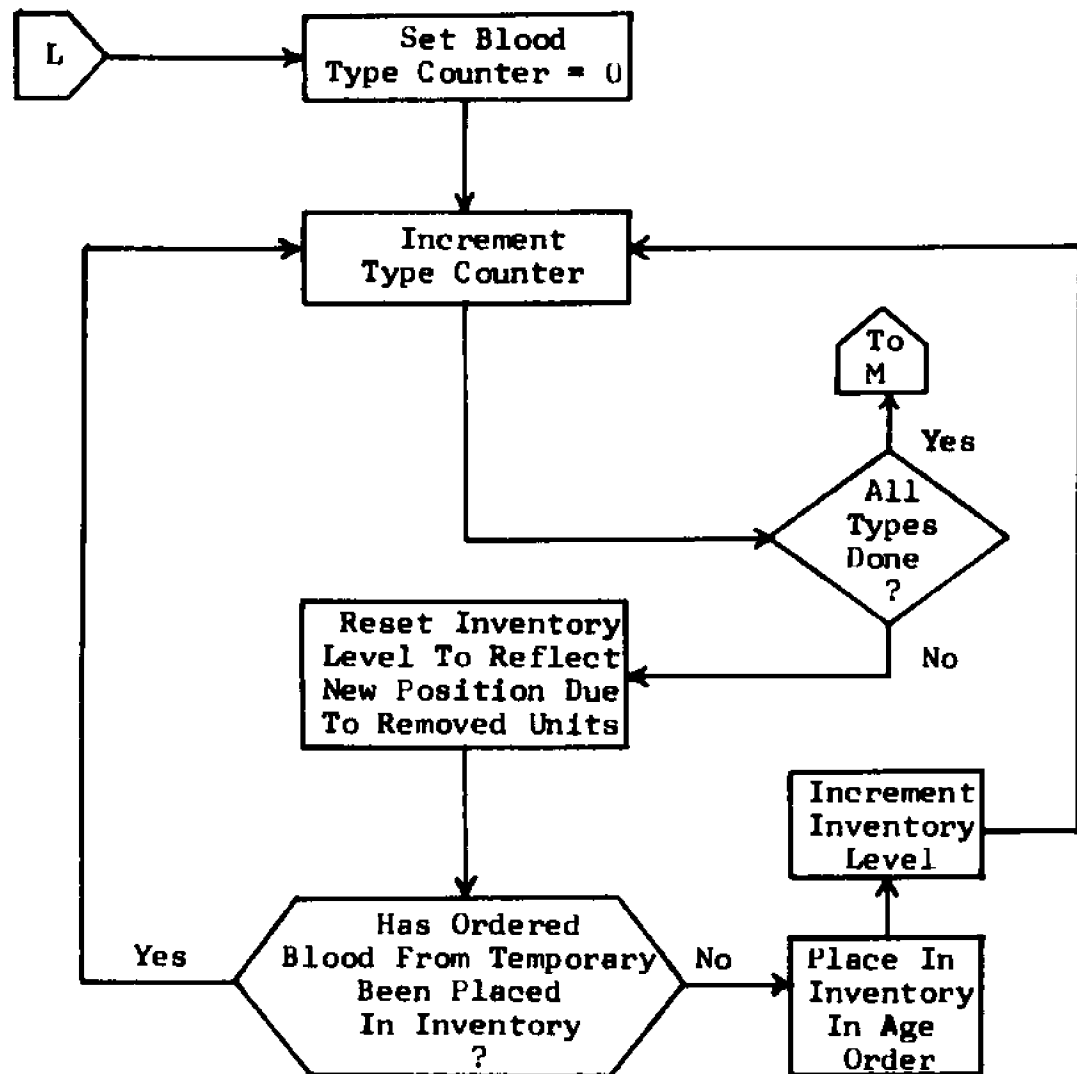
Note: Blood Types are
Processed in the Following
Order--A-,A+,B-,B+,AB-,AB+,
O-,O+, i.e. Rh Negative
Before Rh Positive.



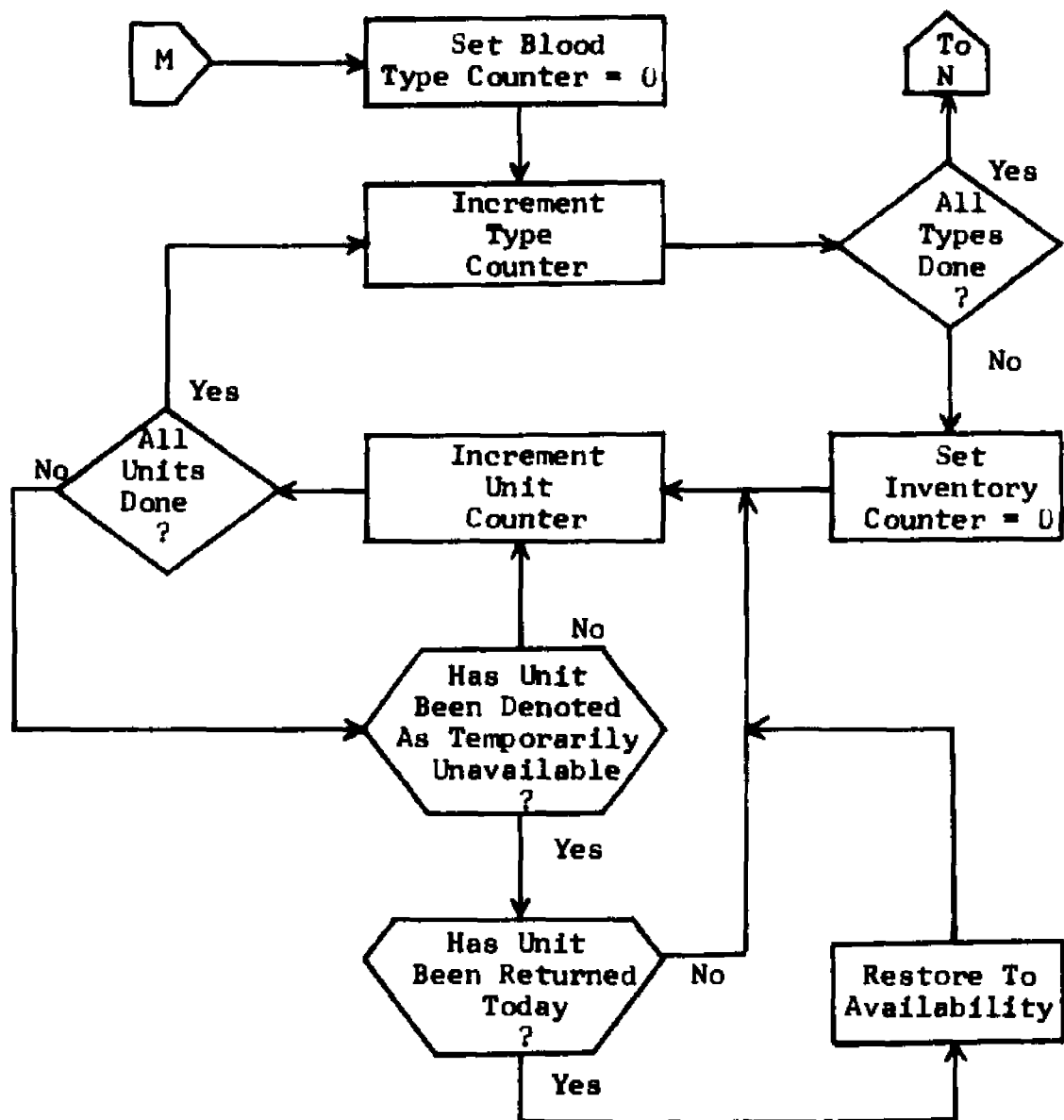
EXPIRATION OF LIFE OF BLOOD



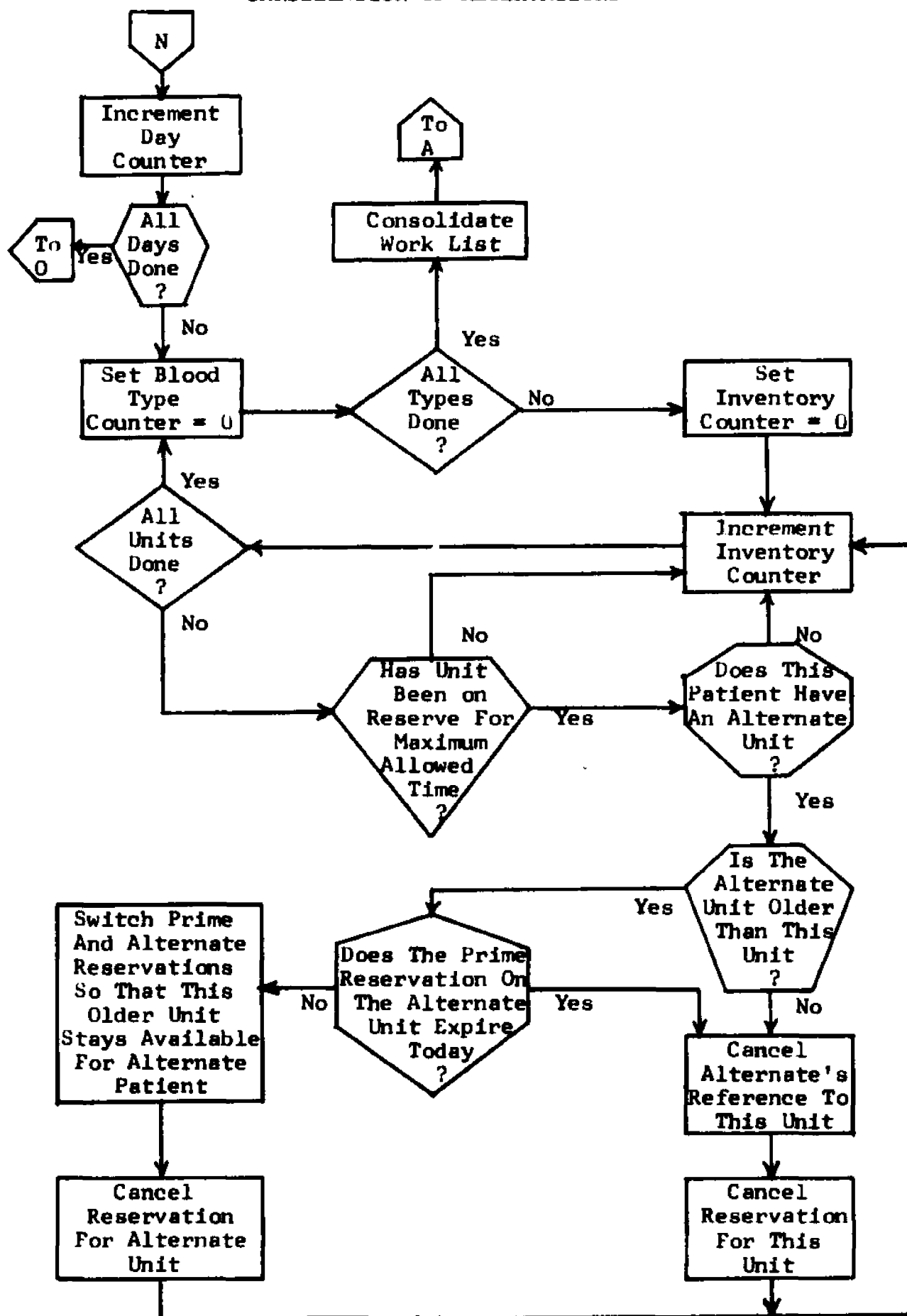
RESET INVENTORY



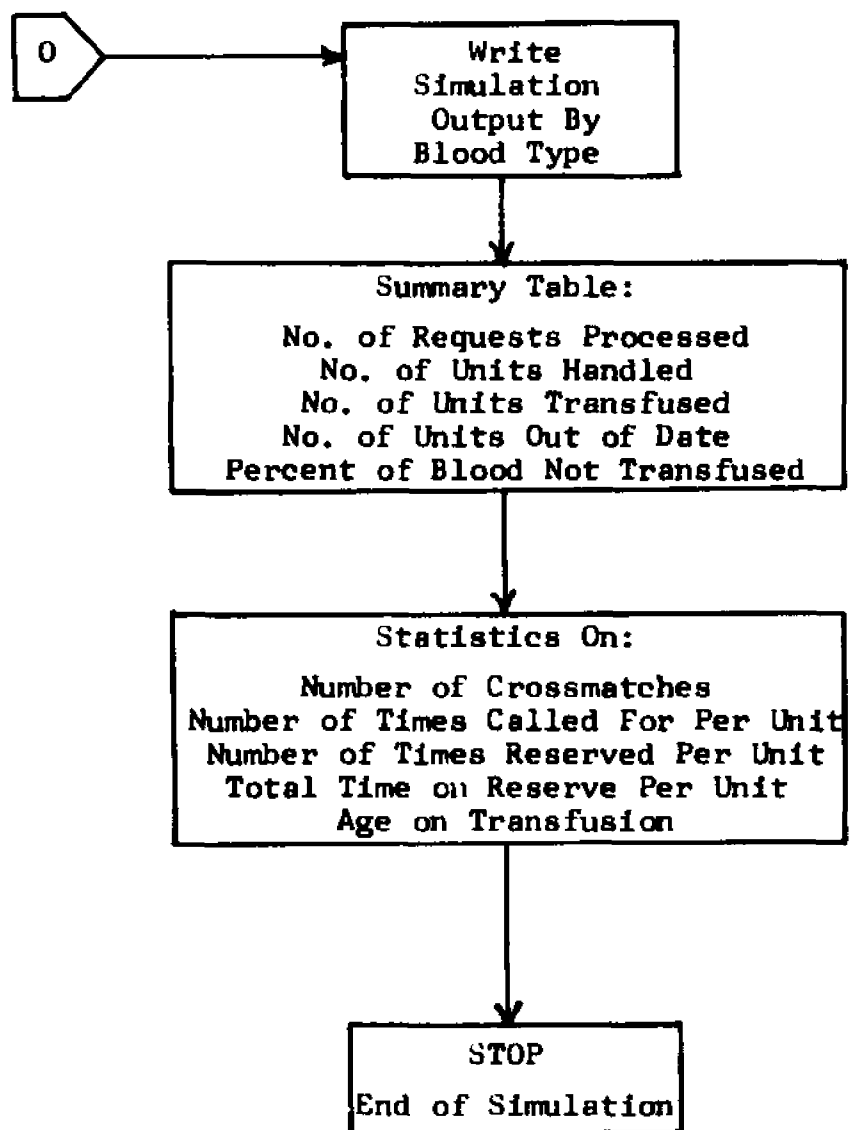
RETURNS OF CALLED FOR BLOOD



CANCELLATION OF RESERVATIONS



OUTPUT



APPENDIX VI**BLOOD BANK SIMULATOR****SAMPLE OUTPUT**

SAMPLE OF FULL DAILY OUTPUT

TODAY IS DAY 47

TAKEN OFF RESERVE	20	0	4	0	4	0	32	2
ORDERED BLOOD	11	3	6	1	2	0	16	1
DONATIONS	0	0	0	0	1	0	1	0
PATIENTS	8	1	4	0	0	0	6	1
NO. OF RESERVATIONS	29	2	5	0	0	0	16	1
CALL FORS	20	2	3	0	0	0	12	1
AGE AT TRANSFUSION	12.83	0.0	17.67	0.0	0.0	0.0	12.10	16.00

EXPIRATION OF LIFE,OUT DATE,CANCEL ,RETURN

1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	2	2	0
8	0	0	0

AGE OF AM INV	10.15	12.18	10.37	14.50	8.87	13.00	9.67	8.17	
NEW INVENTORY	47	11	24	2	15	0	66	11	
RETURNS	2	4	1	0	0	0	2	0	
OUT OF INVENTORY	0	0	0	0	0	0	0	0	
CUM. UNITS EXP.	18	4	13	4	2	3	21	1	
CUM. UNITS HNDLD	274	26	81	8	30	5	347	44	
CUM. PCT. EXP.	6.57	15.38	16.05	50.00	6.67	60.00	6.05	2.27	8.10

SAMPLE OF SUMMARIZED DAILY OUTPUT

TODAY IS DAY 173

CUM. UNITS HNDLD	1423	171	526	51	221	26	1751	195	
CUM. PCT. EXP.	4.29	8.77	13.31	52.94	4.07	57.69	3.43	12.82	6.46

TODAY IS DAY 174

CUM. UNITS HNDLD	1424	171	526	51	224	28	1756	195	
CUM. PCT. EXP.	4.28	8.77	13.31	52.94	4.02	60.71	3.53	12.82	6.54

TODAY IS DAY 175

SPECIAL ORDER FOR 1 UNITS OF BLOOD TYPE, 6

CUM. UNITS HNDLD	1432	174	539	51	225	29	1763	198	
CUM. PCT. EXP.	4.26	8.62	12.99	52.94	4.00	58.62	3.52	12.63	6.48

TODAY IS DAY 176

CUM. UNITS HNDLD	1445	176	543	52	227	29	1768	198	
CUM. PCT. EXP.	4.22	8.52	12.89	53.85	3.96	58.62	3.51	12.63	6.47

TODAY IS DAY 177

CUM. UNITS HNDLD	1453	178	550	53	227	30	1770	200	
CUM. PCT. EXP.	4.27	8.43	12.73	52.83	3.96	56.67	3.56	12.50	6.48

TODAY IS DAY 178

CUM. UNITS HNDLD	1467	180	550	53	227	30	1776	204	
CUM. PCT. EXP.	4.29	8.33	12.73	52.83	3.96	56.67	3.60	12.25	6.49

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = OL

SUMMARY OUTPUT OF BLOOD UTILIZATION

	A+	A-	
NO. OF REQUESTS PROCESSED	4753	552	
NO. OF UNITS OF BLOOD HANDLED	1571	188	
NO. OF UNITS TRANSFUSED	1507	173	
NO. OF UNITS OUT OF DATE	64	15	
PERCENT OF BLOOD NOT TRANSFUSED	4.07	7.98	1

ELATED TIME

TEST 1/3 = OLD BLOOD

UTILIZATION

A-	B+	B-	AB+	AB-	O+	O-	ALL
552	1716	117	630	71	5453	574	13866
188	584	56	242	30	1926	216	4813
173	510	27	233	13	1860	191	4514
15	74	29	9	17	66	25	299
7.98	12.67	51.79	3.72	56.67	3.43	11.57	6.21

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = 0

NUMBER OF CROSS MATCHES PER UNIT

NO OF XM	A+		A-		B+		B
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.
0	1.02	1.02	1.06	1.06	1.37	1.37	8.9
1	26.03	27.05	27.66	28.72	17.81	19.18	28.5
2	17.89	44.94	20.21	48.94	25.68	44.86	33.9
3	17.38	62.32	15.96	64.89	25.17	70.03	14.2
4	18.08	80.39	16.49	81.38	17.64	87.67	10.7
5	11.58	91.98	11.70	93.09	9.25	96.92	1.7
6	5.73	97.71	3.72	96.81	2.57	99.49	1.7
7	1.34	99.05	2.66	99.47	0.51	100.00	0.0
8	0.70	99.75	0.0	99.47	0.0	100.00	0.0
9	0.25	100.00	0.53	100.00	0.0	100.00	0.0
10	0.0	100.00	0.0	100.00	0.0	100.00	0.0
11	0.0	100.00	0.0	100.00	0.0	100.00	0.0
12	0.0	100.00	0.0	100.00	0.0	100.00	0.0
13	0.0	100.00	0.0	100.00	0.0	100.00	0.0
14	0.0	100.00	0.0	100.00	0.0	100.00	0.0
15	0.0	100.00	0.0	100.00	0.0	100.00	0.0
16	0.0	100.00	0.0	100.00	0.0	100.00	0.0
17	0.0	100.00	0.0	100.00	0.0	100.00	0.0
18	0.0	100.00	0.0	100.00	0.0	100.00	0.0
19	0.0	100.00	0.0	100.00	0.0	100.00	0.0
20	0.0	100.00	0.0	100.00	0.0	100.00	0.0
21	0.0	100.00	0.0	100.00	0.0	100.00	0.0
AVERAGE		2.9580		2.8617		2.8048	
VARIANCE		2.9505		2.9702		1.9140	
STD. DEV.		1.7177		1.7234		1.3835	
NO. OF OBS		1571.		188.		584.	

EST 1/3 = OLD BLOOD

R UNIT

[illegible]

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = OLD BLO

NUMBER OF TIMES CALLED FOR PER UNIT

NO OF CF	A+		A-		B+		B-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
0	0.70	0.70	4.26	4.26	5.65	5.65	35.71	35.
1	72.12	72.82	75.00	79.26	73.29	78.94	58.93	94.
2	20.88	93.70	18.09	97.34	18.49	97.43	3.57	98.
3	4.96	98.66	2.13	99.47	2.23	99.66	1.79	100.
4	1.02	99.68	0.53	100.00	0.34	100.00	0.0	100.
5	0.25	99.94	0.0	100.00	0.0	100.00	0.0	100.
6	0.06	100.00	0.0	100.00	0.0	100.00	0.0	100.
7	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
8	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
9	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
10	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
11	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
12	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
13	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
14	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
15	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
16	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
17	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
18	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
19	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
20	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
21	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.
AVERAGE		1.3450		1.1968		1.1832		0.71
VARIANCE		0.4437		0.3177		0.3277		0.30
STD. DEV.		0.6661		0.5636		0.5725		0.61
NO. OF OBS		1571.		188.		584.		!

EST 1/3 = OLD BLOOD

PER UNIT

[illegible]

HOSPITAL BLOOD BANK SIMULAT

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = OLD BLO

NUMBER OF TIMES RETURNED PER UNIT

NO RETD	A+		A-		B+		B-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
0	71.23	71.23	78.19	78.19	74.32	74.32	80.36	80.36
1	21.64	92.87	17.02	95.21	21.23	95.55	16.07	96.43
2	5.16	98.03	3.72	98.94	3.94	99.49	3.57	100.00
3	1.46	99.49	1.06	100.00	0.17	99.66	0.0	100.00
4	0.38	99.87	0.0	100.00	0.34	100.00	0.0	100.00
5	0.13	100.00	0.0	100.00	0.0	100.00	0.0	100.00
6	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
7	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
8	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
9	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
10	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
11	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
12	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
13	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
14	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
15	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
16	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
17	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
18	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
19	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
20	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
21	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
AVERAGE		0.3851		0.2766		0.3099		0.2283
VARIANCE		0.4991		0.3384		0.3440		0.2411
STD. DEV.		0.7064		0.5817		0.5865		0.4910
NO. OF OBS		1571.		188.		584.		584.

ED TIME

T 1/3 = OLD BLOOD

UNIT

	B-		AB+		AB-		O+		O-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
32	80.36	80.36	79.75	79.75	83.33	83.33	75.03	75.03	86.57	86.57
55	16.07	96.43	19.42	99.17	16.67	100.00	18.17	93.20	11.11	97.69
49	3.57	100.00	0.41	99.59	0.0	100.00	5.19	98.39	1.39	99.07
66	0.0	100.00	0.41	100.00	0.0	100.00	1.30	99.69	0.46	99.54
00	0.0	100.00	0.0	100.00	0.0	100.00	0.21	99.90	0.46	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.10	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
99		0.2321		0.2149		0.1667		0.3380		0.1713
40		0.2497		0.2018		0.1389		0.4512		0.2531
65		0.4997		0.4492		0.3727		0.6717		0.5031
4.		56.		242.		30.		1926.		216.

HOSPITAL BLOOD BANK SIMULATION

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = OLD BLOOD

NUMBER OF TIMES DOUBLE CROSS MATCHED PER UNIT

NO DB XM	A+		A-		B+		B-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
0	14.19	14.19	19.68	19.68	15.24	15.24	55.36	55.36
1	32.46	46.66	38.30	57.98	34.42	49.66	37.50	92.86
2	21.96	68.62	23.94	81.91	21.23	70.89	7.14	100.00
3	14.26	82.88	8.51	90.43	13.53	84.42	0.0	100.00
4	7.38	90.26	5.32	95.74	7.36	91.78	0.0	100.00
5	4.39	94.65	3.72	99.47	4.97	96.75	0.0	100.00
6	2.55	97.20	0.0	99.47	1.20	97.95	0.0	100.00
7	1.65	98.85	0.0	99.47	1.37	99.32	0.0	100.00
8	0.45	99.30	0.53	100.00	0.34	99.66	0.0	100.00
9	0.51	99.81	0.0	100.00	0.0	99.66	0.0	100.00
10	0.19	100.00	0.0	100.00	0.34	100.00	0.0	100.00
11	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
12	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
13	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
14	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
15	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
16	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
17	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
18	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
19	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
20	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
21	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
AVERAGE		2.0757		1.5585		1.9469		0.5179
VARIANCE		3.0732		1.7998		2.7044		0.3925
STD. DEV.		1.7531		1.3416		1.6445		0.6265
NO. OF OBS		1571.		188.		584.		56.

DEST 1/3 = OLD BLOOD

CROSS MATCHED PER UNIT

[illegible]

HOSPITAL BLOOD BANK SIMULATION

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = OLD BLOOD

TOTAL TIME SPENT ON RESERVE PER UNIT

DAYS RES	A+		A-		B+		B-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
0	17.57	17.57	16.49	16.49	10.62	10.62	26.79	26.79
1	13.37	30.94	15.96	32.45	13.18	23.80	8.93	35.71
2	12.35	43.28	12.77	45.21	13.87	37.67	19.64	55.36
3	10.76	54.04	11.17	56.38	14.04	51.71	10.71	66.07
4	9.87	63.91	12.23	68.62	12.16	63.87	8.93	75.00
5	11.39	75.30	8.51	77.13	13.18	77.05	16.07	91.07
6	8.72	84.02	5.85	82.98	9.25	86.30	3.57	94.64
7	5.67	89.69	7.98	90.96	5.65	91.95	3.57	98.21
8	4.01	93.70	5.32	96.28	2.91	94.86	0.0	98.21
9	3.12	96.82	1.06	97.34	3.08	97.95	1.79	100.00
10	1.53	98.34	0.53	97.87	0.86	98.80	0.0	100.00
11	1.02	99.36	1.06	98.94	0.51	99.31	0.0	100.00
12	0.38	99.75	1.06	100.00	0.51	99.83	0.0	100.00
13	0.19	99.94	0.0	100.00	0.0	99.83	0.0	100.00
14	0.0	99.94	0.0	100.00	0.17	100.00	0.0	100.00
15	0.0	99.94	0.0	100.00	0.0	100.00	0.0	100.00
16	0.0	99.94	0.0	100.00	0.0	100.00	0.0	100.00
17	0.0	99.94	0.0	100.00	0.0	100.00	0.0	100.00
18	0.0	99.94	0.0	100.00	0.0	100.00	0.0	100.00
19	0.0	99.94	0.0	100.00	0.0	100.00	0.0	100.00
20	0.0	99.94	0.0	100.00	0.0	100.00	0.0	100.00
21	0.06	100.00	0.0	100.00	0.0	100.00	0.0	100.00
AVERAGE		3.5379		3.3936		3.6644		2.5893
VARIANCE		8.4281		7.8770		6.7743		5.0635
STD. DEV.		2.9031		2.8066		2.6028		2.2502
NO. OF OBS		1571.		188.		584.		56.

DD TIME

1/3 = OLD BLOOD

ER UNIT

	B-		AB+		AB-		O+		O-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
2	26.79	26.79	19.01	19.01	10.00	10.00	14.85	14.85	19.44	19.44
0	8.93	35.71	17.77	36.78	6.67	16.67	12.77	27.62	15.28	34.72
7	19.64	55.36	13.22	50.00	30.00	46.67	13.91	41.54	17.59	52.31
1	10.71	66.07	13.64	63.64	13.33	60.00	13.29	54.83	10.65	62.96
7	8.93	75.00	16.94	80.58	20.00	80.00	13.60	68.43	15.28	78.24
5	16.07	91.07	9.09	89.67	3.33	83.33	10.64	79.08	7.41	85.65
0	3.57	94.64	5.37	95.04	10.00	93.33	8.05	87.12	5.09	90.74
5	3.57	98.21	2.07	97.11	6.67	100.00	5.19	92.32	3.24	93.98
6	0.0	98.21	0.83	97.93	0.0	100.00	3.12	95.43	1.39	95.37
5	1.79	100.00	0.41	98.35	0.0	100.00	2.23	97.66	1.39	96.76
0	0.0	100.00	0.83	99.17	0.0	100.00	0.99	98.65	1.39	98.15
1	0.0	100.00	0.41	99.59	0.0	100.00	0.57	99.22	0.93	99.07
3	0.0	100.00	0.0	99.59	0.0	100.00	0.36	99.58	0.0	99.07
3	0.0	100.00	0.0	99.59	0.0	100.00	0.16	99.74	0.46	99.54
0	0.0	100.00	0.0	99.59	0.0	100.00	0.16	99.90	0.46	100.00
0	0.0	100.00	0.0	99.59	0.0	100.00	0.0	99.90	0.0	100.00
0	0.0	100.00	0.0	99.59	0.0	100.00	0.0	99.90	0.0	100.00
0	0.0	100.00	0.0	99.59	0.0	100.00	0.05	99.95	0.0	100.00
0	0.0	100.00	0.0	99.59	0.0	100.00	0.0	99.95	0.0	100.00
0	0.0	100.00	0.0	99.59	0.0	100.00	0.0	99.95	0.0	100.00
0	0.0	100.00	0.0	99.59	0.0	100.00	0.0	99.95	0.0	100.00
0	0.0	100.00	0.41	100.00	0.0	100.00	0.05	100.00	0.0	100.00
4		2.5893		2.7686		3.1000		3.4444		2.9398
3		5.0635		6.2109		3.7567		7.2459		7.1029
8		2.2502		2.4922		1.9382		2.6918		2.6651
.		56.		242.		30.		1926.		216.

HOSPITAL BLOOD BANK SIMULATION

TEST RUN 26 WEEKS SIMULATED TIME

DOUBLE CROSSMATCHING: OLDEST 1/3 = OLD BLOOD

AGE ON TRANSFUSION

AGE-DAYS	A+		A-		B+		B-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
0	0.20	0.20	0.0	0.0	0.20	0.20	0.0	0.0
1	0.33	0.53	0.0	0.0	0.0	0.20	0.0	0.0
2	0.53	1.06	1.73	1.73	0.39	0.59	0.0	0.0
3	1.26	2.32	0.58	2.31	0.20	0.78	0.0	0.0
4	2.12	4.45	0.0	2.31	0.20	0.98	0.0	0.0
5	2.59	7.03	4.05	6.36	0.98	1.96	0.0	0.0
6	2.72	9.75	2.89	9.25	1.76	3.73	0.0	0.0
7	4.05	13.80	2.31	11.56	0.78	4.51	3.70	3.70
8	3.98	17.78	8.09	19.65	0.39	4.90	3.70	7.41
9	3.19	20.97	6.94	26.59	2.75	7.65	0.0	7.41
10	5.18	26.14	5.78	32.37	2.55	10.20	7.41	14.81
11	7.30	33.44	7.51	39.88	6.67	16.86	0.0	14.81
12	6.83	40.28	6.36	46.24	4.90	21.76	3.70	18.52
13	10.22	50.50	4.05	50.29	7.25	29.02	7.41	25.93
14	11.48	61.98	7.51	57.80	13.14	42.16	3.70	29.63
15	12.21	74.19	4.62	62.43	12.55	54.71	3.70	33.33
16	8.03	82.22	9.25	71.68	11.57	66.27	3.70	37.04
17	5.84	88.06	8.09	79.77	9.02	75.29	3.70	40.74
18	4.11	92.17	8.09	87.86	8.24	83.53	3.70	44.44
19	3.45	95.62	6.36	94.22	8.24	91.76	11.11	55.56
20	2.32	97.94	4.05	98.27	4.12	95.88	29.63	85.19
21	2.06	100.00	1.73	100.00	4.12	100.00	14.81	100.00
AVERAGE		12.7956		12.9942		14.8706		16.8148
VARIANCE		18.1586		21.3237		13.3127		18.4475
STD. DEV.		4.2613		4.6178		3.6487		4.2951
NO. OF OBS		1507.		173.		510.		27.

ED TIME

T 1/3 = OLD BLOOD

	B-		AB+		AB-		O+		O-	
	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.	PCT.	CUM.
20	0.0	0.0	0.0	0.0	0.0	0.0	0.16	0.16	0.0	0.0
20	0.0	0.0	2.15	2.15	0.0	0.0	0.05	0.22	1.05	1.05
59	0.0	0.0	0.43	2.58	0.0	0.0	0.05	0.27	1.57	2.62
78	0.0	0.0	2.58	5.15	0.0	0.0	0.32	0.59	0.0	2.62
98	0.0	0.0	0.0	5.15	7.69	7.69	0.54	1.13	3.66	6.28
96	0.0	0.0	1.72	6.87	0.0	7.69	1.51	2.63	2.62	8.90
73	0.0	0.0	0.86	7.73	0.0	7.69	2.26	4.89	5.24	14.14
51	3.70	3.70	3.00	10.73	0.0	7.69	2.42	7.31	9.42	23.56
90	3.70	7.41	5.15	15.88	0.0	7.69	4.62	11.94	6.81	30.37
55	0.0	7.41	5.15	21.03	0.0	7.69	4.57	16.51	7.33	37.70
20	7.41	14.81	6.01	27.04	7.69	15.38	6.45	22.96	11.52	49.21
36	0.0	14.81	4.72	31.76	7.69	23.08	9.35	32.31	4.19	53.40
76	3.70	18.52	7.30	39.06	7.69	30.77	9.35	41.67	8.38	61.78
02	7.41	25.93	7.30	46.35	0.0	30.77	12.96	54.62	6.28	68.06
16	3.70	29.63	7.73	54.08	0.0	30.77	10.54	65.16	6.28	74.35
71	3.70	33.33	6.01	60.09	7.69	38.46	9.89	75.05	7.85	82.20
27	3.70	37.04	9.87	69.96	7.69	46.15	7.90	82.96	3.66	85.86
29	3.70	40.74	8.58	78.54	0.0	46.15	5.70	88.66	4.71	90.58
53	3.70	44.44	4.72	83.26	15.38	61.54	4.46	93.12	0.52	91.10
76	11.11	55.56	9.44	92.70	7.69	69.23	2.63	95.75	2.62	93.72
38	29.63	85.19	4.29	97.00	15.38	84.62	2.58	98.33	3.14	96.86
00	14.81	100.00	3.00	100.00	15.38	100.00	1.67	100.00	3.14	100.00
06		16.8148		13.4292		15.7692		13.0376		11.2565
27		18.4475		22.6999		24.6390		13.5674		21.2169
17		4.2951		4.7644		4.9638		3.6834		4.6062
0.		27.		233.		13.		1860.		191.

APPENDIX VII

SIMULATOR INPUT REQUIREMENTS

General Instructions

All variables which begin with the letters I - N must be integer values. All integers are to be punched right justified within the appropriate columns.

All variables with any letters other than I - N are treated as real numbers. The program will assume the decimal point is between the first and second column in the field if none is punched, i.e., xxxxx will be read as x.xxxx. If a decimal is punched in one of the columns within the field, this will override the implicit decimal; i.e., xxx.x will be read as xxx.x.

Data Set 1 - Case Parameters (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	Blank	Unused
6-10	NDAYS	Length of simulation run in days + 21, e.g., if it is desired to simulate 60 days enter 81.
11-15	NUNIT	Establishes transient period - all units received before this elapsed date are ignored in accumulating statistics. Note: Simulator starts on day 21.
16-20	NOLD	Reciprocal of the proportion of units defined as "old" when using double crossmatching, e.g., if NOLD = 3, the oldest 33% of each type will be "old".
21-25	NAGE	Age of Rh negative blood which may be transfused to Rh positive patients. If this option is not desired set NAGE = 22.

Data Set 1 (cont'd)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
26-30	NDBLA	Age restriction on double crossmatching. Simulation will attempt to double crossmatch all units of NDBLA age or older. To disable this restriction set NDBLA=0.
31-35	NDBLN	Number of units restriction on double crossmatching. Simulation will attempt to double crossmatch the first NDBLN units of each type. To disable this restriction set NDBLN=99999.
36-40	NDBLP	Percent old restriction on double crossmatching. Simulation will attempt to double crossmatch the oldest NDBLP percent of units of each type. To disable this restriction set NDBLP=100.

Data Set 2 - Seeds for Random
Number Generator (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	IY(1)	The program uses a different seed for each type of random event that is generated. This is done so that the effects of different policies can be compared easily because the random events which are not affected by the policy can be made identical from run to run by using the same seeds. Note: IY(i) must be an <u>odd</u> integer from 1 to 5 digits.
6-10	IY(2)	
11-15	IY(3)	
.	.	
.	.	
71-75	IY(15)	

Data Set 3 - Parameters for Storing
Inventory in Computer Memory (1 card)

This variable is used in order to be able to store all units of blood in one large array even though there are eight different blood types. This variable is necessary to separate the different types in that array. The number of locations set aside for each blood type can be calculated from the following equation:

$$\text{Number of locations for type (i)} = \text{IBEG}(i+1) - \text{IBEG}(i)$$

Data Set 3 (cont'd)

It is estimated that you should provide from $1\frac{1}{2}$ to 2 times the locations required for the exact desired inventory level.

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	IBEG(1)	Beginning of first blood type.
6-10	IBEG(2)	Beginning of second blood type.
.	.	.
36-40	IBEG(8)	Beginning of last blood type.
41-45	IBEG(9)	End of last blood type. This value must coincide with the dimension of the array IBEG, currently set at 500.

Data Set 4 - Number of Units in Inventory
at Start of Simulation (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XINVN(1,1)	Number of units of 1st blood type.
6-10	Blank	Unused.
11-15	XINVN(1,2)	Number of units of 2nd blood type
16-20	Blank	Unused.
.	.	This variable is used to determine the number of units of each blood type in inventory at the end of the day before the simulation begins.
.	.	
.	.	
.	.	
71-75	XINVN(1,8)	Number of units of 8th blood type.
76-80	Blank	Unused.

Data Set 5 - Parameters for Generating
the Time Between the Creation
of a Reservation and its
Expiration if the Unit
is Not Called For
(1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XTOR(1,1)	Value of k for 1st blood type.
6-10	XTOR(2,1)	Value of p for 1st blood type.
11-15	XTOR(1,2)	Value of k for 2nd blood type.

Data Set 5 (cont'd)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
16-20	XTOR(2,2)	Value of p for 2nd blood type.
21-25	XTOR(1,3)	Value of k for 3rd blood type. (etc.)
.	.	The simulator generates reservation durations from the following probability distribution:
.	.	$f(x) = k g(x) + (1-k) h(x)$
.	.	where x is the duration in days;
.	.	$g(x) = 1$ for $x = 2$,
.	.	$= 0$ otherwise;
.	.	$h(x) = p(1-p)^{x-1}$ for $x \geq 1$.
71-75	XTOR(1,8)	Value of p for 8th blood type.
76-80	XTOR(2,8)	Value of k for 8th blood type.

Data Set 6 - Proportion of Beginning
Inventory Which is on Reserve
(1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	RSVPB(1)	Proportion of starting inventory of each type which is put on reserve to initialize inventory status at the beginning of a run.
6-10	RSVPB(2)	
.	.	
36-40	RSVPB(8)	

Data Set 7 - Age Distribution of Inventory
at the Beginning of a Simulation
(16 cards - 2 cards for each blood type)

Card 1:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XINVAG(1,1)	Proportion of units 0 days old.
6-10	XINVAG(2,1)	Proportion of units 1 day or less old.
11-15	XINVAG(3,1)	Proportion of units 2 days or less old.
.	.	.
51-55	XINVAG(11,1)	Proportion of units 10 days or less old.

Data Set 7 (cont'd)Card 2:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XINVAG(12,i)	Proportion of units 11 days or less old.
6-10	XINVAG(13,i)	Proportion of units 12 days or less old.
.	.	.
.	.	.
51-55	XINVAG(22,i)	Proportion of units 21 days or less old. (This value must be 1.000)

Data Set 8 - Desired Inventory Level (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	IDES(1)	Desired inventory of blood type 1.
6-10	IDES(2)	Desired inventory of blood type 2.
.	.	.
.	.	.
36-40	IDES(8)	Desired inventory of blood type 8.

Data Set 9 - Age Distribution of Blood
Received When Ordered from Central Sources
(16 cards - 2 cards for each blood type)

The following set of 2 cards must be included for each of the eight blood types.

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XORDAG(1,i)	Proportion of units 0 days old.
6-10	XORDAG(2,i)	Proportion of units 1 day or less old.
11-15	XORDAG(3,i)	Proportion of units 2 days or less old.
.	.	.
.	.	.
51-55	XORDAG(11,i)	Proportion of units 10 day or less old.

Data Set 9 (cont'd)Card 2:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XORDAG(12,1)	Proportion of units 11 days or less old.
6-10	XORDAG(13,1)	Proportion of units 12 days or less old.
.	.	.
51-55	XORDAG(22,1)	Proportion of units 21 days or less old. (This value must be 1.00000)

Data Set 10 - Parameters for Generating the
Number of Units Donated Per Day (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XNDNR(1)	Mean number of units of blood type 1 donated per day.
6-10	XNDNR(2)	Mean number of units of blood type 2 donated per day.
.	.	(The number of units donated is generated by the simulator using
.	.	$f(x) = e^{-u} u^x / x!$
.	.	where x is the number donated on a particular day;
.	.	u is the mean number donated.)
36-40	XNDNR(8)	Mean number of units of blood type 8 donated per day.

Data Set 11 - Parameters for Generating the
Number of Patients Requesting
Blood Per Day (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XNPAT(1,1)	Mean number of patients requesting blood type 1 on weekdays.
6-10	XNPAT(2,1)	Mean number of patients requesting blood type 1 on weekends.
11-15	XNPAT(1,2)	Mean number of patients requesting blood type 2 on weekdays.

Data Set 11 (cont'd)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
16-20	XNPAT(2,2)	Mean number of patients requesting blood type 2 on weekends.
.	.	(The number of patients is generated by the simulator using
.	.	$f(x) = e^{-u} u^x / x!$
.	.	where x is the number of patients on a particular day;
.	.	u is the mean number of patients.)
71-75	XNPAT(1,8)	Mean number of patients requesting blood type 8 on weekdays.
76-80	XNPAT(2,8)	Mean number of patients requesting blood type 8 on weekends.

Data Set 12 - Parameters for Generating the
Time Between Request and Reservation
Crossmatching (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	REQXM(1)	Reciprocal of the proportion of reservations which are made on the same day as the request (elapsed days = 0) for each blood type = average elapsed days + 1.
6-10	REQXM(2)	
11-15	REQXM(3)	
.	.	(The simulator generates the elapsed time using
.	.	$f(x) = p(1-p)^x ; x \geq 0$
.	.	where x is the elapsed days;
.	.	p is the proportion of reservations made on the same day.)
36-40	REQXM(8)	

Data Set 13 - Parameters for Generating the
Number of Units Requested by
Each Patient (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XNUNT(1,1)	Value of k for blood type 1.
6-10	XNUNT(2,1)	Value of p for blood type 1.
11-15	XNUNT(1,2)	Value of k for blood type 2.

Data Set 13 (cont'd)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
16-20	XNUNT(2,2)	Value of p for blood type 2.
.	.	(The simulator generates order sizes, i.e., number of units requested, from the following probability distribution:
.	.	$f(x) = k g(x) + (1-k) h(x)$
.	.	where x is the order size;
.	.	$g(x) = 1$ for $x = 2$,
.	.	$= 0$, otherwise;
.	.	$h(x) = p(1-p)^{x-1}$ for $x \geq 1$.)
71-75	XNUNT(1,8)	Value of k for blood type 8.
76-80	XNUNT(2,8)	Value of p for blood type 8.

Data Set 14 - Parameters for Generating the
Time Between Crossmatching and
Call For (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XCF(1,1)	Proportion of units called for on same day = k.
6-10	XCF(2,1)	Reciprocal of proportion of units called for on next day = $1/p$ = average elapsed days of those units not called for on same day.
11-15	XCF(1,2)	A value of k and $1/p$ must be included for each blood type.
16-20	XCF(2,2)	
.	.	(The simulator generates elapsed time using
.	.	$f(x) = k g(x) + (1-k) h(x)$
.	.	where x is the elapsed days;
.	.	$g(x) = 1$ for $x = 0$,
.	.	$= 0$, otherwise;
.	.	$h(x) = p(1-p)^{x-1}$ for $x \geq 1$.)
71-75	XCF(1,8)	
76-80	XCF(2,8)	

Data Set 15 - Parameters for Generating the
Times Between Call For
and Return (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XRET(1)	Reciprocal of the proportion of returns which are made on the same day as the call for (elapsed days = 0 for each blood type) equals average elapsed days + 1. The simulator generates the elapsed time using $f(x) = p(1-p)^x, x \geq 0$ where x is the elapsed days; p is the proportion of returns made on the same day.
6-10	XRET(2)	
.	.	
.	.	
.	.	
.	.	
.	.	
36-40	XRET(8)	

Data Set 16 - Maximum Number of Units Which Can Be
Requested by a Patient Per Day (1 card)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	NMAX(1)	The maximum allowable order size for each blood type. This is necessary since it is theoretically possible to generate in the simulation very large orders which do not occur in the actual blood bank. This value was taken to be the largest order size found in the data collected for each blood type.
6-10	NMAX(2)	
.	.	
.	.	
.	.	
.	.	
.	.	
36-40	NMAX(8)	

Data Set 17 - Distributions of the Number of Units
Called For Conditional on the Number Requested
(10 cards - one distribution per card for
each order size from 1 to 10 units)

Each card has the following format:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XNCF(1,i)	Probability of calling for 0 units given i units ordered.
6-10	XNCF(2,i)	Probability of calling for 1 or less units given i units ordered.

Data Set 17 (cont'd)

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
11-15	XNCF(3,i)	Probability of calling for 2 or less units given i units ordered.
.	.	.
.	.	.
.	XNCF(i+1,i)	Probability of calling for i or less units given i units ordered. (This last entry on each card must be 1.000.)

Data Set 18 - Distributions of the Number of Units
Returned Conditional on the Number Called For
(10 cards - one distribution per card for each
quantity called for from 1 to 10 units)

Each card has the following format:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1-5	XNRET(1,i)	Probability of returning 0 units given i units called for.
6-10	XNRET(2,i)	Probability of returning 1 or less units given i units called for.
11-15	XNRET(3,i)	Probability of returning 2 or less units given i units called for
.	.	.
.	.	.
.	XNRET(i+1,i)	Probability of returning i or less units given i units called for. (The last entry on each card must be 1.000.)

Data Set 19 - Replaces Data Set 17 when the "Special"
User Option is Used - Conditional Distributions
of the Number of Units Called For the Non-
"Special" Users and the Comparable Dis-
tributions for the "Special" Users

(10 cards - one for each 'regular'

patient order size from 1-10.

Order size for "special"

patients is limited to

six in the program but

the data cards can

accomodate eight.

Each card has the following format:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1 - 5	XNCF(1,i)	Same as XNCF(1,i) but for "regular" patients only.
6 - 10	XNCF(2,i)	Same as XNCF(2,i) but for "regular" patients only.
:	:	:
5(i-1)+1 - 5i	XNCF(i,i)	Same as XNCF(i,i) but for "regular" patients only.
5i+1 - 5(i+1)	XNCF(i+1,i)	Same as XNCF(i+1,i) but for "regular" patients only. (The i+1st entry must be 1.0 on all cards)
5(i+1)+1 - 5(i+2)	XNCF(1,j)	Probability of calling for 0 units given j = 9 - i units ordered by "special" users.
:	:	:
51 - 55	XNCF(j+1,j)	Probability of calling for j or less units given j = 9 - i units ordered by "special" users. (This entry must be 1.0)

Note: In addition to the above, columns 51-55 on card number 9 of this set must contain the proportion of all patients that are to be considered as "special" users.

Data Set 20 - Replaces Data Set 18 when the "Special"
User Option is Used - Conditional Distributions
of the Number of Units Called For all Patients
except "Special" Users and the Comparable
Distributions for the "Special" Users.

(10 cards - one for each 'regular'
 patient quantity called for from
 1-10) (Returns for "Special"
 patients are limited to six
 but the data cards can
 accomodate up to eight)

Each card has the following format:

<u>Columns</u>	<u>Variable</u>	<u>Explanation</u>
1 - 5	XNRET(1,i)	Same as XNRET(1,i) but for "regular" patients only.
6 - 10	XNRET(2,i)	Same as XNRET(2,i) but for "regular" patients only.
.	.	
5(i-1)+1 - 5i	XNRET(i,i)	Same as XNRET(i,i) but for "regular" patients only.
5i+1 - 5(i+1)	XNRET(i+1,i)	Same as XNRET(i+1,i) but for "regular" patients only. (The i+1st entry must be 1.0 on all cards)
5(i+1)+1 - 5(i+2)	XNRET(i,j)	Probability of returning 0 units given j = 9-i units called for by "special" users.
5(i+2)+1 - 5(i+3)	XNRET(2,j)	Probability of returning 1 or less units given j = 9-i units called for by "special" users.
5i - 55	XNRET(j+1,j)	Probability of returning j or less units given j = 9-i units called for by "special" users. (This entry must be 1.0)

Data Set 21 - Alphameric Information for
the Page and Table Heading

Card 1:

Col. 1 - 32 Title to appear at the top of each page of output.

Cards 2 and 3:

Col. 1 - 64 Two lines of additional Alphameric information serving as sub-titles which appear under the title on each page and can be used to determine the parameters of the run.

Card 4:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1-8	NO OF XM	Column headings for use by the output routine.
9-16	NO OF CF	
17-24	NO RETD	
25-32	NO DBXM	
33-40	DAYS RES	
41-48	AGE-DAYS	

Card 5:

<u>Columns</u>	<u>Contents</u>	<u>Explanation</u>
1-8	PCT.CUM.	Column headings for use by the output program.
9-16	PCT.CUM.	
.	.	
.	.	
57-64	PCT.CUM.	

Data Set 20 (cont'd)Cards 6 - 12:

Titles of the seven tables output at the end of the simulation run.

ColumnsRecommended Contents

1-64	NUMBER OF CROSSMATCHES PER UNIT
1-64	NUMBER OF TIMES CALLED FOR PER UNIT
1-64	NUMBER OF TIMES RETURNED PER UNIT
1-64	NUMBER OF TIMES DOUBLE-CROSSMATCHED PER UNIT
1-64	TOTAL TIME SPENT ON RESERVE PER UNIT
1-64	AGE ON TRANSFUSION
1-64	SUMMARY OUTPUT OF BLOOD UTILIZATION

Card 13:ColumnsContents

1-4	Alphameric definition of blood type 1 (e.g. A+)
5-8	Alphameric definition of blood type 2 (e.g. A-)
9-12	.
.	.
.	.
29-32	Alphameric definition of blood type 8
33-36	Alphameric definition for total (e.g. ALL)

APPENDIX VIII

MAXIMUM LIKELIHOOD ESTIMATES OF THE
PARAMETERS OF A CLASS OF
COMPOSITE DISTRIBUTIONS

Maximum likelihood estimators are desirable because these estimators possess the following characteristics:

1. They are consistent.
2. They are sufficient.
3. They are asymptotically efficient.
4. Their distributions tend to normality as n increases.

Many of the estimators which are commonly used, such as the means of the normal, Poisson and binomial distribution and regression coefficients using the least squares method are maximum likelihood estimators. Although maximum likelihood estimators are not necessarily unbiased (e.g. the maximum likelihood estimate of the variance of a normal distribution is $\Sigma(x-\bar{x})^2/n$, which is a biased estimate), the bias will tend to zero with large n , if the estimate is biased. The estimators listed above are all unbiased estimators.

Maximum likelihood estimates are obtained by first determining the probability of the sample that was obtained. This function is called the likelihood function. Next, the likelihood function (or its logarithm) is differentiated with respect to the parameter(s). The maximum likelihood estimates of the parameter(s) are then obtained by equating the derivatives to zero and solving.

These estimates are, therefore, those which maximize the probability (likelihood) of obtaining the particular sample that was actually obtained.

If $f(x)$ is a composite distribution of the form:

$$f(x) = k g(x) + (1-k) h(x)$$

where $g(x) = 1$, for $x = c$; $g(x) = 0$, otherwise;

$$h(x) = p(1-p)^{x-1} \text{ for } x \geq 1,$$

then $f(x)$ has two parameters; k and p , and it is necessary to estimate them from the observed data. If a sample of size n has been taken then the likelihood function, $y = f(x_1, x_2, \dots, x_n)$ which is the probability of obtaining the specific set of observations that was obtained, is

$$Y = \prod_{i=1}^n [k g(x_i) + (1-k) p(1-p)^{x_i-1}].$$

Since different values of c lead different likelihood functions it is advisable to consider three cases separately:

Case 1, $c = 0$;

Case 2, $c = 1$;

Case 3, $c > 1$.

Case 1, $c = 0$

Letting m = the number of observations where $x_i = c = 0$, $n-m$ is the number of observations where $x_i \neq c \neq 0$, or $x \geq 1$.

$$\begin{aligned} Y &= \prod_{i=1}^m [k] \prod_{i=1}^{n-m} [(1-k) p(1-p)^{x_i-1}] \\ &= k^m (1-k)^{n-m} p^{n-m} (1-p)^{\sum x_i - (n-m)} \end{aligned}$$

$$\ln Y = Y' = m \ln k + (n-m) \ln(1-k) + (n-m) \ln p \\ + (x_1 - n + m) \ln(1-p)$$

$$\frac{dY'}{dp} = \frac{n-m}{p} - \frac{\sum x_1 - n + m}{1-p} = 0$$

$$n-m-np+mp-p \sum x_1 + np - mp = 0$$

$$n - m = p \sum x_1$$

$$p = \frac{n-m}{\sum x_1}$$

Thus, the maximum likelihood estimator of p is the reciprocal of the mean of the non-zero observations. Since the $x_1 \geq 1$, the mean of the non-zero items will be ≥ 1 and therefore $0 < p \leq 1$.

$$\frac{dY'}{dk} = \frac{m}{k} - \frac{n-m}{1-k} = 0$$

$$\frac{m}{k} = \frac{n-m}{1-k}$$

$$m-mk = nk - mk$$

$$m = nk$$

$$k = \frac{m}{n}$$

Thus, the maximum likelihood estimator of k is the observed relative frequency for $x = 0$. Since $0 \leq \frac{m}{n} \leq 1$, k also satisfies the requirements to be a probability.

Since $0 < p \leq 1$, $k(x)$ is a true probability distribution and since $0 < k < 1$, $f(x)$ is simply a probabilistic weighting of two probability distributions which is therefore, also a probability distribution.

Case 2, c = 1

$$Y = [k + (1-k)p]^m \prod_{i=1}^{x-1} [(1-k)p(1-p)^{x_i-1}]$$

$$= [k + (1-k)p]^m (1-k)^{n-m} p^{n-m} (1-p)^{\sum_{i=1}^{x-1} x_i - (n-m)}$$

$$\ln Y = Y' = m \ln[k + (1-k)p] + (n-m) \ln(1-k) + (n-m) \ln p$$

$$+ \left[\sum_{i=1}^{x-1} x_i - (n-m) \right] \ln(1-p)$$

$$(1.1) \quad \frac{dY'}{dp} = \frac{m(1-p)}{k + (1-k)p} + \frac{n-m}{p} - \frac{\sum_{i=1}^{x-1} x_i - (n-m)}{1-p} = 0$$

$$(1.2) \quad \frac{dY'}{dk} = \frac{m(1-p)}{k + (1-k)p} - \frac{n-m}{1-k} = 0$$

from (1.1)

$$\frac{m(1-k)}{k + (1-k)p} = \frac{\sum_{i=1}^{x-1} x_i - (n-m)}{1-p} - \frac{n-m}{p}$$

from (1.2)

$$\frac{m(1-k)}{k + (1-k)p} = \frac{n-m}{1-p}$$

Since $\sum x_i$ for the $x=1 = m$, we have

$$\frac{n-m}{1-p} = \frac{\sum x - m - (n-m)}{1-p} - \frac{n-m}{p}$$

$$\frac{n-m}{p} = \frac{\sum x - 2n - m}{1-p}$$

$$(n-m)(1-p) = p(\sum x - 2n - m)$$

$$n - m = p(\sum x - n)$$

$$p = \frac{n-m}{\sum x - n} = \frac{1-\frac{m}{n}}{\bar{x}-1}$$

Thus, the maximum likelihood estimator of p is the reciprocal of the mean of those observations for which $x_i > 1$, taken after each x_i has been reduced by 1. That is, if $y = x-1$, then the m x_i 's for $x = 1$ will become zero and the distribution of the $n-m$ x_i 's for $x > 1$ will become a distribution of y having the standard geometric form starting at $y = 1$. The parameter of this geometric distribution $p = \frac{1}{y}$ is then equivalent to $p = \frac{1 - (m/n)}{\bar{x} - 1}$ since $y = x-1$ and $1 - \frac{m}{n}$ is the fraction of the observations which are non-zero. Since there will be at least one $x_i > 1$, $\bar{x}$ will be greater than 1 and $\frac{m}{n}$ will be less than 1 and therefore $0 < p < 1$.

Substituting the value of p into equation (1.2) we have:

$$\frac{m(1-p)}{k + (1-k)p} = \frac{n-m}{1-k}$$

$$m(1-p)(1-k) = (n-m)[k + (1-k)p]$$

$$m(1-p-k+pk) = (n-m)[k + p - pk]$$

$$m = nk + np - npk$$

$$m - np = k(n-np)$$

$$\frac{m - np}{n - np} = k$$

$$\frac{m/n - p}{1-p} = k$$

Since $0 < p < 1$, the denominator is positive and as long as the observed relative frequency for $x = 1$ is greater than the estimate of p , the numerator will be positive and since $m/n < 1$, the value of k will satisfy $0 < k < 1$. Since $0 < p < 1$, $h(x)$ is a probability distribution and since $0 < k < 1$, $f(x)$ is also a probabilistic weighting of two probability distributions, which is, therefore, also a probability distribution.

Case 3, $c > 1$

Letting m = the number of observations where $x_i = c > 1$,
 $n-m$ is the number of observations where $x_i \neq c$.

$$Y = \left[k + (1-k) p(1-p)^{c-1} \right]^m \prod_{x_i \neq c} \left[(1-k) p(1-p)^{x_i-1} \right]$$

$$= \left[k + (1-k) p(1-p)^{c-1} \right]^m (1-k)^{n-m} p^{n-m} (1-p)^{\sum_{x_i \neq c} x_i - (n-m)}$$

Taking logarithms:

$$\ln Y = Y' = m \ln \left[k + (1-k) p(1-p)^{c-1} \right] + (n-m) \ln(1-k)$$

$$+ (n-m) \ln p + \left[\sum_{x_i \neq c} x_i - (n-m) \right] \ln(1-p)$$

To maximize, we take the partial derivatives with respect to p and k and equate to 0.

$$(2.1) \quad \frac{dY'}{dp} = \frac{m(1-k) [-p(1-p)^{c-2} + (1-p)^{c-1}]}{[k + (1-k) p(1-p)^{c-1}]} + \frac{n-m}{p} - \frac{\sum_{x_i \neq c} x_i - (n-m)}{1-p} = 0$$

$$(2.2) \quad \frac{dY'}{dk} = \frac{m[1 - p(1-p)^{c-1}]}{[k + (1-k) p(1-p)^{c-1}]} - \frac{n-m}{1-k} = 0$$

from (2.1)

$$\frac{m(1-k)}{[k + (1-k) p(1-p)^{c-1}]} = \frac{p \left[\sum_{x_i \neq c} x_i - (n-m) \right] - (1-p)(n-m)}{p(1-p) [-p(1-p)^{c-2} + (1-p)^{c-1}]}$$

from (2.2)

$$\frac{m(1-k)}{[k + (1-k) p(1-p)^{c-1}]} = \frac{n-m}{1 - p(1-p)^{c-1}}$$

Since $\sum_m x_i$ for the $x_i = c = cm$ we have

$$\frac{p \left[\sum x_i - n - (c-1)m \right]}{p(1-p) \left[-p(1-p)^{c-2} + (1-p)^{c-1} \right]} = \frac{n-m}{1-p(1-p)^{c-1}}$$

$$\frac{p \sum x_i - cpm - n + m}{p(1-p)^{c-1} (1-2p)} = \frac{n-m}{1-p(1-p)^{c-1}}$$

Crossmultiplying

$$(n-m) p(1-p)^{c-1} (1-2p) = \left[1 - p(1-p)^{c-1} \right] (p \sum x_i - cpm - n + m)$$

$$p^2(1-p)^{c-1}(2m - 2n + \sum x_i - cm) = p \sum x_i - cpm - n + m$$

$$p^2(1-p)^{c-1}(2m - 2n + \sum x_i - cm) + p(cm - \sum x_i) + n - m = 0$$

This is a polynomial of degree $(c+1)$, which can be solved for p .

Specifically, let $c = 2$

$$p^2(1-p)(2m - 2n + \sum x_i - 2m) = p \sum x_i - 2pm - n + m$$

$$p^3(\sum x_i - 2n) - p^2(\sum x_i - 2n) + p(\sum x_i - 2m) + n - m = 0$$

Dividing through by n we have

$$(\bar{x} - 2)p^3 - (\bar{x} - 2)p^2 + (\bar{x} - 2\frac{m}{n})p - 1 + \frac{m}{n} = 0$$

which is a polynomial of the form

$$ap^3 - ap^2 + bp - c = 0$$

$$\text{where } a = \bar{x} - 2$$

$$b = \bar{x} - 2\frac{m}{n}$$

$$c = 1 - \frac{m}{n}$$

In order for $f(x)$ to be a probability distribution it is necessary that estimates of the parameters exist such that $0 \leq p \leq 1$. The following section demonstrates that this is true.

Case 1, $\bar{x} \geq 2$

$$f(p) = ap^3 - ap^2 + bp - c$$

$$f(p) = + - + - \therefore \text{Maximum of 3 positive roots}$$

$$f(-p) = - - - - \therefore \text{Maximum of 0 negative roots}$$

There are either 3 positive roots or 1 positive and 2 imaginary roots.

$$\frac{df(x)}{dx} = 3ap^2 - 2ap + b = 0$$

$$p = \frac{2a \pm \sqrt{4a^2 - 2ab}}{6a}$$

Since $b = x - 2\frac{m}{n}$ and $a = \bar{x} - 2$

and $m/n < 1$

$$\therefore b > a$$

$$ab > a^2$$

$$12ab > 4a^2$$

$$p = \frac{-2a \pm \sqrt{-\text{quantity}}}{6a}$$

Therefore, there are no local maxima or minima and the function can only cross the axis at one point. Therefore, there must be 1 positive and 2 imaginary roots.

$$f(0) = -c$$

$$f(1) = a - a + b - c = b - c$$

$$= \bar{x} - 2\frac{m}{n} - (1 - \frac{m}{n})$$

$$= \bar{x} - (1 + \frac{m}{n})$$

Since $\bar{x} \geq 2$ and $m/n < 1$

$$(1 + \frac{m}{n}) < 2$$

$$\therefore \bar{x} - (1 + \frac{m}{n}) > 0$$

Thus, the function crosses the axis between 0 and 1 and there exists a solution for p such that $0 < p < 1$.

Case 2. $\bar{x} < 2$

$$f(p) = -ap^3 + ap^2 + bp - c$$

where a is now defined as $2 - \bar{x}$ to keep it positive

$$f(p) = - + + - ; \text{ Maximum of 2 positive roots}$$

$$f(-p) = + + - - ; \text{ Maximum of 1 negative root}$$

There are either 1 negative and 2 positive roots or 1 negative and 2 imaginary roots.

$$\frac{df(x)}{dx} = -3ap^2 + 2ap + bc$$

$$x = \frac{-2a \pm \sqrt{4a^2 + 12ab}}{-6a}$$

$$b = \bar{x} - 2\frac{m}{n} > 0$$

$$a = 2 - \bar{x} > 0$$

$$\therefore 4a^2 + 12ab > 0$$

Thus, there are 2 real roots to the quadratic and therefore there is a local maximum and a local minimum to the cubic.

The cubic has 3 real roots, which means it has 1 negative root and 2 positive roots. Local maximum of the cubic occurs at

$$\begin{aligned}
 x &= \frac{-2a - \sqrt{4a^2 + 12ab}}{-6a} \\
 &= \frac{-2a - 2\sqrt{a^2 + 3ab}}{6a}
 \end{aligned}$$

and since $b > a$

$$\begin{aligned}
 x &> \frac{-2a - 2\sqrt{a^2 + 3a^2}}{-6a} \\
 &> \frac{-2a - 2\sqrt{4a^2}}{-6a} \\
 &> \frac{a + 2a}{3a}
 \end{aligned}$$

$$x > 1$$

Since the maximum of the cubic occurs at $x > 1$, one of the roots must occur after the maximum and this root must therefore be > 1 .

One root has to be negative, one root is greater than 1, we must therefore show that the other root is between 0 and 1.

If the only observed values of x were $x = 1$ and $x = 2$ and since $m/n = \text{percent of } x_1 = 2$
 then $1 - m/n = \text{percent of } x_1 = 1$.

Therefore, the mean of the observed data would be $\sum x p(x)$

$$\begin{aligned}
 &= 1\left(1 - \frac{m}{n}\right) + 2\left(\frac{m}{n}\right) \\
 &= 1 - \frac{m}{n} + 2\frac{m}{n} \\
 &= 1 + \frac{m}{n}
 \end{aligned}$$

Since there are some $x_1 > 2$

$$\bar{x} \text{ must be } > 1 + \frac{m}{n}$$

$$f(0) = -c$$

$$f(1) = -a + a + b - c = b - c$$

$$= \bar{x} - 2 \frac{m}{n} - (1 - \frac{m}{n})$$

$$= \bar{x} - (1 + \frac{m}{n})$$

which must be > 0 .

Therefore, the function crosses the axis between 0 and 1 and thus there must be a root such that $0 < p < 1$. Having found a value for p such that $0 < p < 1$, we can find the estimator of k by substituting the estimate of p into equation (2.2) and solving for k . Thus for $c = 2$, we have

$$\frac{m[1-p(1-p)]}{k + (1-k)p(1-p)} = \frac{n-m}{1-k}$$

$$(1-k)m[1-p(1-p)] = (n-m)[k + (1-k)p(1-p)]$$

$$m(1-p + p^2) - mk(1-p + p^2) = (n-m)k + (n-nk-m+mk)p(1-p)$$

$$m = nk + np - np^2 - nkp + nkp^2$$

$$\frac{m}{n} - p + p^2 = k - kp + kp^2$$

$$k = \frac{m/n - p + p^2}{1 - p + p^2}$$

$$(2.5) \quad k = \frac{m/n - p(1-p)}{1 - p(1-p)}$$

Since $0 < p < 1$, $p(1-p) > 0$ and $k < 1$. In addition, a sufficient condition for $k > 0$ is that $m/n > \frac{1}{4}$ since the maximum value of $p(1-p)$ is $\frac{1}{4}$. Since all the observed relative frequency distributions in which this model was applied satisfied this condition, the maximum likelihood estimators, $\hat{p}$ and $\hat{k}$, of p and k respectively are such that

$$f(x) = \hat{k} g(x) + (1-\hat{k}) h(x)$$

where $g(x) = 1$, for $x = 2$, $g(x) = 0$, otherwise;

and $h(x) = \hat{p}(1-\hat{p})^{x-1}$ for $x \geq 1$

satisfies the requirements of a probability distribution.

It can be shown that estimators of p and k which are obtained using the observed mean ($\bar{x}$) and the observed relative frequency of $x=2$ (i.e. $\frac{m}{n}$) as conditions which must be satisfied are equivalent to the maximum likelihood estimators.

Thus we have:

$$\bar{x} = E(x)$$

$$\bar{x} = k E[x|g(x)] + (1-k) E[x|h(x)]$$

Since $g(x) = 1$ for $x = 2$; $g(x) = 0$, otherwise;

$$E[x|g(x)] = 2$$

Since $h(x) = p(1-p)^{x-1}$, $E[x|h(x)] = 1/p$.

Therefore, the first condition yields the following equation:

$$(3.1) \quad \bar{x} = 2k + (1-k) 1/p.$$

Also $m/n = P(x = 2)$

$$= k P[x=2|g(x)] + (1-k) P[x=2|h(x)].$$

Since $g(x) = 1$ for $x = 2$, $P[x=2|g(x)] = 1$.

Since $h(x) = p(1-p)^{x-1}$ $P[x=2|h(x)] = p(1-p)$.

Therefore the second condition yields the following equation:

$$(3.2) \quad m/n = k + (1-k) p(1-p).$$

Using (3.1) we find

$$k = \frac{\bar{x}p - 1}{2p - 1}$$

Substituting this into (3.2) we have

$$m/n = \frac{\bar{x}p-1}{2p-1} + \left[1 - \frac{\bar{x}p-1}{2p-1}\right] p(1-p)$$

$$m/n = \frac{1-\bar{x}p}{1-2p} + \frac{\bar{x}p-2p}{1-2p} p(1-p)$$

$$m/n = \frac{1 - \bar{x}p + (\bar{x}p - 2p) p(1-p)}{1 - 2p}$$

$$m/n - 2p(m/n) = 1 - \bar{x}p(-1 + p - p^2) - 2p^2 + 2p^3$$

$$\bar{x}p(1 - p + p^2) = 1 - (m/n) + 2p(m/n) - 2p^2 + 2p^3$$

$$\bar{x}p - \bar{x}p^2 + \bar{x}p^3 = 1 - (m/n) + 2p(m/n) - 2p^2 + 2p^3$$

$$(3.3) \quad p^3(\bar{x} - 2) - p^2(\bar{x} - 2) + p(\bar{x} - 2\frac{m}{n}) - 1 + m/n = 0$$

Which is identical to equation (2.3) obtained when using the maximum likelihood method and this estimator of p will therefore be identical to the maximum likelihood estimator.

If the solution to equation (3.3) is then substituted into equation (3.2) we have:

$$m/n = k + (1-k) p(1-p)$$

$$m/n = k + p(1-p) - kp(1-p)$$

$$m/n = p(1-p) = k - kp(1-p)$$

$$m/n = p(1-p) = k[1-p(1-p)]$$

$$(3.4) \quad k = \frac{m/n - p(1-p)}{1 - p(1-p)}$$

Which is identical to equation (2.5) obtained when using the maximum likelihood method and this estimator of k will therefore be identical to the maximum likelihood estimator.

APPENDIX IX

CHOICE OF A "GOODNESS OF FIT" TEST
AND ITS APPLICATION

In statistical terminology a test of "goodness of fit" is a test to determine if a set of data obtained from a sample could have come from a hypothesized population. In this study the goodness of fit test was used to determine if data generated in the simulation using a hypothesized model would provide a meaningful reproduction of the observed events and their timing. Two of the best known and most widely used tests of goodness of fit are the Chi-square test and the Kolmogorov-Smirnov test. The advantages and disadvantages of these two procedures relative to the types of data associated with this study are discussed in this appendix.

Sample size

The distribution of the chi-square test statistic is only known for asymptotically large samples, and the behavior of the test statistic is not exactly known for all sample sizes. Thus, the chi-square test becomes an approximate test for all sample sizes and for small samples, when the assumptions are clearly violated, it is not applicable at all. In this study much of the data on patient demand and almost all the data on the rarer blood types are based on relatively small samples, thus rendering the chi-square test inappropriate in these cases. Conversely, the Kolmogorov-Smirnov test requires no assumption as to sample size and is applicable to all random samples.

Estimation of parameters from the data

In this study, the hypothesized distributions were specified only as far as their distribution type, with the parameters to be estimated from the sample data. The chi-square test provides an allowance for this estimation of the parameters from the data by making an appropriate reduction in the degrees of freedom associated with the test. Conversely, the Kolmogorov-Smirnov test requires that the hypothesized distribution be completely specified in advance and provides no method of adjusting for parameters calculated from the data.

Massey¹ indicated that the effect of adjusting the hypothesized distribution to the sample's parameters would be to reduce the critical value of the test statistic. Thus, if the test were performed using the tabled critical values it would be overly conservative.² Then, if the hypothesis were still rejected, it could be safely concluded that the hypothesized distribution did not "fit" the observed data.

Additional work toward determining the effect of estimating parameters from observed data has been done by Lilliefors.^{3,4} When

¹F. J. Massey, "The Kolmogorov-Smirnov Test for Goodness of Fit," Journal of the American Statistical Association, Vol 46 (1951), pp. 68-78

²Conservativeness, in the statistical sense means that the level of significance is overstated. That is, the probability of rejecting the hypothesis when it is true is really less than the tabular level, thus there is less probability of committing a Type I error.

³H. W. Lilliefors, "On the Kolmogorov-Smirnov Test for the Exponential Distribution with Mean Unknown," Journal of the American Statistical Association, Vol. 64, No. 325, March 1969, pp. 387-389.

⁴H. W. Lilliefors, "On the Kolmogorov-Smirnov Test for

using the sample mean and variance when hypothesizing normality, Lilliefors found that the critical values should be approximately two-thirds of those in the standard table for the same level of significance. This would make the values tabled at $\alpha = .20$ approximately the same as those Lilliefors found appropriate for $\alpha = .01$. Perhaps more appropriately, since most of the distributions observed in this study are highly skewed when the parameter of a hypothesized exponential distribution is estimated from the data, the appropriate critical values for $\alpha = .05$ are approximately equal to those tabled for $\alpha = .20$. Since all of Lilliefors work was of an empirical nature, it is not known whether the differences between the normal and the exponential case are due to the distribution shape or the number of parameters estimated or both. However, the work does indicate the nature and magnitude of the adjustment of the test statistic that is necessary if the Kolmogorov-Smirnov statistic is to be used when parameters have been calculated from the data.

Continuous vs. discrete distributions

When the data are continuous, they must be grouped into intervals, with a corresponding loss of information for the chi-square test to be applicable. The Kolmogorov-Smirnov test, being defined specifically for continuous data, makes use of each individual observation and therefore does not suffer any loss of information due to grouping.

When the data are discrete in nature, as in all of the

Normality with Mean and Variance Unknown," Journal of the American Statistical Association, Vol. 62, No. 318, June 1967, pp. 399-402.

distributions in this study, the chi-square test is directly applicable as long as sufficiently large theoretical frequencies belong in each discrete class to allow the use of the chi-square distribution as an appropriate test statistic. Although discrete, almost all of the observed distributions (as well as the hypothesized models) are extremely positively skewed, having a long right hand tail with relatively few values in each cell in the tail. Thus, these cells must be combined until a sufficient frequency is obtained, rendering the last cell to be of the form "all values greater than x". In these cases, the chi-square test again suffers a loss of information due to grouping. In addition, in many cases, the number of classes that remain, after creating classes with sufficient observations, do not permit estimation of a critical value if parameters have been estimated from the data. The critical value of this test is the value of chi-square for a given α from the distribution having "degrees of freedom" equal to the number of classes (after combining) minus the number of parameters estimated from the data minus 1. Thus, if only two cells are available after combining frequencies and one parameter has been estimated from the data, or if three cells remain and two parameters have been estimated from the data, there is no way of obtaining a critical value for the test and therefore the test becomes meaningless.

The distribution of the critical value of the Kolmogorov-Smirnov test has only been defined when the hypothesized population is continuous, so that the application of this test to discrete data represents a compromise of its underlying assumptions. However,

the test may be used in this application with the proviso that the consequence is again to make the test more conservative, i.e., the true value of α may be smaller than but not larger than the tabular value. This result was stated by Darling.⁵

Relative power of the tests

One of the main advantages of the Kolmogorov-Smirnov test over the chi-square test is that it seems to be a uniformly more powerful test (when both tests are applicable) for any sample size.⁶ Massey⁷ showed that the Kolmogorov-Smirnov test was more powerful than the chi-square test in the ability to detect a distance shift from the hypothesized distribution for sample sizes from 200 to 2000. Kac, Kiefer and Wolfowitz⁸ have shown that it is asymptotically more powerful than the chi-square test of goodness of fit. Lilliefors,⁹ using Monte-Carlo experimentation showed that the Kolmogorov-Smirnov test of normality when the parameters were calculated from the data was more powerful than the chi-square test in detecting distributional alternatives for sample size of 20. Lilliefors¹⁰ stated that the Kolmogorov-Smirnov test for an exponential distribution, using parameters from the data, was found by Monte-Carlo methods to

⁵D. A. Darling, "The Kolmogorov-Smirnov, Cramér-von Mises Tests," Annals of Mathematical Statistics, Vol. 28 (1957), pp. 823-838.

⁶Lilliefors, "Kolmogorov-Smirnov Test for Normality," p. 399.

⁷Massey, "Kolmogorov-Smirnov Test," p. 75.

⁸M. Kac, J. Kiefer, and J. Wolfowitz, "On Tests of Normality and Other Tests of Goodness of Fit Based on Distance Methods," The Annals of Mathematical Statistics, Vol. 26 (1955), pp. 189-211.

⁹Lilliefors, "Test for Normality," p. 401.

¹⁰Lilliefors, "Test for Exponential Distribution," p. 389.

be more powerful than the chi-square test in detecting distributional alternatives for sample sizes of 10, 20 and 50.

Conclusions

Due to problems of too small a sample size or too few meaningful cells, the chi-square test would not be applicable in almost half of the tests of goodness of fit to be performed in this study. The Kolmogorov-Smirnov test can be performed in all cases, although the exact effects of estimating the parameters from the data and the use of discrete data on the Kolmogorov-Smirnov test are not known. It is known that these conditions will make the critical values more conservative (smaller α level) than stated. Finally, in all cases that have been reported in the literature, the Kolmogorov-Smirnov test has been found to be more powerful than the corresponding chi-square test. For these reasons, the Kolmogorov-Smirnov test has been used to test the hypothesized models for goodness of fit, with the significance level set at $\alpha = .20$ (the highest α value for which tabular values are available) to compensate for the anticipated conservativeness of the test due to the estimation of parameters from the data as well as the discreteness of the data.

Nature of the Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test statistic, $D_{\max}$, is the maximum difference (ignoring signs) between the points on the cumulative step-function of an observed sample and the corresponding points (for equal values of the random variable) on the cumulative distribution of the hypothesized distribution.

Thus, if $F(x)$ = the proportion of observations less than
or equal to x in the hypothesized distribution,

and $S_n(x)$ = the proportion of observations less than or equal to x in the observed data,

$$\text{then } D_{\max} = \max_x \left| S_n(x) - F(x) \right| .$$

The sampling distribution of this statistic is known and the critical values of $D_{\max}$ under the null hypothesis for several values of α has been tabulated for $n \leq 35$ and asymptotic formulas have given for $n > 35$. One such table is given in Massey.¹¹

Results of using the Kolmogorov-Smirnov test of goodness of fit

The following tables provide a summary of the application of the Kolmogorov-Smirnov procedure to testing the applicability of the theoretical models in representing the observed distributions.

¹¹Massey, "Kolmogorov-Smirnov Test," p. 7.

TABLE A9-1

NUMBER OF UNITS DONATED PER DAY BY BLOOD TYPE
THEORETICAL MODEL: POISSON^a

	A+	A-	B+	B-	AB+	AB-	O+	O-
Obsvd. Mean = Theor. Mean	2.1540	0.3585	0.7009	0.1122	0.3551	0.0190	2.4673	0.3458
Observed Variance	2.8693	0.5319	0.7399	0.1183	0.4576	0.0187	3.1758	0.4131
Theoretical Variance	2.1540	0.3585	0.7009	0.1122	0.3551	0.0190	2.4673	0.3458
Number of Observations	104	106	107	107	107	105	107	107
$D_{\max}$	.0754	.0570	.0218	.0037	.0313	.0008	.0556	.0336
Critical $D_{\max}$ $\alpha = .05$	.1334	.1321	.1315	.1315	.1315	.1327	.1315	.1315
Critical $D_{\max}$ $\alpha = .20$	.1049	.1039	.1034	.1034	.1034	.1044	.1034	.1034

^a $f(x) = e^{-u} u^x / x!$

TABLE A9-2a

NUMBER OF PATIENTS PER DAY - SUNDAY TO THURSDAY
THEORETICAL MODEL: POISSON^a

	A+	A-	B+	B-	AB+	AB-	O+	O-
Obsvd. Mean = Theor. Mean	15.580	1.971	6.235	0.629	2.357	0.400	16.855	1.886
Observed Variance	19.630	1.850	7.138	0.599	1.885	0.301	16.214	2.190
Theoretical Variance	15.580	1.971	6.235	0.629	2.357	0.400	16.855	1.886
Number of Observations	69	68	69	70	70	70	69	70
D _{max}	.067	.085	.039	.033	.084	.042	.052	.033
Critical D _{max} $\alpha = .05$	.160	.160	.160	.160	.160	.160	.160	.160
Critical D _{max} $\alpha = .20$	.129	.130	.129	.128	.128	.128	.129	.128

^a $f(x) = e^{-u} u^x / x!$

TABLE A9-2b

NUMBER OF PATIENTS PER DAY - FRIDAY AND SATURDAY
THEORETICAL MODEL: POISSON^a

	A+	A-	B+	B-	AB+	AB-	O+	O-
Obsvd. Mean = Theor. Mean	9.286	1.393	3.786	0.464	1.393	0.107	8.808	1.286
Observed Variance	8.201	1.358	3.582	0.333	2.173	0.173	7.442	1.175
Theoretical Variance	9.286	1.393	3.786	0.464	1.393	0.107	8.808	1.286
Number of Observations	28	28	28	28	28	28	28	28
D _{max}	.064	.024	.040	.060	.108	.034	.119	.038
Critical D _{max} $\alpha = .05$	.242	.242	.242	.242	.242	.242	.242	.242
Critical D _{max} $\alpha = .20$	.190	.190	.190	.190	.190	.190	.190	.190

^a $f(x) = e^{-u} u^x / x!$

TABLE A9-3

NUMBER OF UNITS REQUESTED PER PATIENT PER DAY
 THEORETICAL MODEL: $f(x) = k g(x) + (1-k) h(x) *$

	A+	A-	B+	B-	AB+	AB-	O+	O-
Obsvd. Mean = Theor. Mean	2.0880	2.0205	2.0813	1.5762	2.0381	1.6522	2.2353	2.3275
Observed Variance	1.6777	1.4944	1.7598	0.5234	2.2569	0.6008	1.9668	2.8686
Theoretical Variance	1.5992	1.2826	1.6858	0.6171	1.6028	0.6272	2.1239	2.5354
K	.340	.390	.285	.187	.257	.270	.348	.330
P	.4687	.4917	.4731	.6762	.4875	.6565	.4236	.4018
Number of Observations	1352	195	566	52	210	23	1483	171
$D_{\max}$	.011	.010	.016	.011	.019	.014	.012	.024
Critical $D_{\max}$ $\alpha = .05$	.037	.097	.057	.190	.094	.264	.035	.104
Critical $D_{\max}$ $\alpha = .20$	.029	.077	.045	.148	.074	.220	.028	.082

* $g(x) = 1$ for $x = 2$, $g(x) = 0$ otherwise.
 $h(x) = p(1-p)^{x-1}$ for $x \geq 1$.

TABLE A9-4

TIME FROM REQUEST TO CROSSMATCH IN DAYS
THEORETICAL MODEL: SHIFTED GEOMETRIC^a

	A+	A-	B+	B-	AB+	AB-	O+	O-
Obsvd. Mean = Theor. Mean	0.1359	0.1020	0.1274	0.1486	0.1860	0.2432	0.1237	0.1703
Observed Variance	0.1463	0.1036	0.1278	0.1557	0.2167	0.3559	0.1532	0.2114
Theoretical Variance	0.1544	0.1125	0.1436	0.1707	0.2206	0.3024	0.1390	0.1994
P	.8804	.9074	.8870	.8706	.8432	.8043	.8899	.8544
Number of Observations	2568	343	1209	74	371	37	3355	317
D _{max}	.006	.003	.006	.006	.009	.019	.004	.007
Critical D _{max} $\alpha = .05$	.027	.073	.039	.150	.071	.210	.024	.076
Critical D _{max} $\alpha = .20$	.021	.058	.030	.124	.056	.180	.018	.060

^a $f(x) = p(1-p)^x$ for $x \geq 0$.

TABLE A9-5

TIME FROM CROSSMATCH TO CALL FOR IN DAYS
 THEORETICAL MODEL: $f(x) = k g(x) + (1-k) h(x) *$

	A+	A-	B+	B-	AB+	AB-	O+	O-
Observed Mean = Theor. Mean	0.4685	0.4233	0.4884	0.3953	0.4302	0.1818	0.5038	0.3594
Observed Variance	0.3920	0.3938	0.4432	0.2447	0.4375	0.1636	0.4404	0.4053
Theoretical Variance	0.3912	0.3707	0.4385	0.2390	0.3790	0.1489	0.4313	0.3793
K	.594	.632	.588	.605	.626	.818	.573	.703
P	.868	.870	.839	1.000	.866	1.000	.848	.828
Number of Observations	1080	163	561	43	179	11	1441	128
$D_{\max}$	.001	.014	.014	.000	.043	.000	.007	.048
Critical $D_{\max}$ $\alpha = .05$	.041	.107	.057	.200	.102	.391	.036	.120
Critical $D_{\max}$ $\alpha = .20$	.033	.084	.045	.163	.080	.307	.028	.095

* $g(x) = 1$ where $x = 0$, $g(x) = 0$ otherwise.

$h(x) = p(1-p)^{x-1}$ where $x \geq 1$.

TABLE A9-6

TIME FROM CALL FOR TO RETURN IN DAYS
THEORETICAL MODEL: SHIFTED GEOMETRIC^a

	A+	A-	B+	B-	AB+	AB-	O+	O-
Observed Mean = Theor. Mean	0.2462	0.1707	0.2770	0.1111	0.2500	0.0000	0.2437	0.3695
Observed Variance	0.3447	0.1451	0.5146	0.1111	0.5297	0.0000	0.2755	0.2422
Theoretical Variance	0.3068	0.1999	0.3540	0.1235	0.3125	0.0000	0.3031	0.5075
P	.802	.854	.783	.900	.800	1.000	.804	.730
Number of Observations	329	41	152	9	60	3	398	27
D _{max}	.005	.025	.048	.011	.067	.000	.015	.100
Critical D _{max} $\alpha = .05$	.075	.210	.112	.432	.170	.708	.068	.242
Critical D _{max} $\alpha = .20$	.059	.167	.087	.339	.138	.565	.054	.190

^a $f(x) = p(1-p)^x$ for $x \geq 0$.

TABLE A9-7

TIME FROM CROSSMATCH TO TAKEN OFF RESERVE IN DAYS
 THEORETICAL MODEL: $f(x) = k g(x) + (1-k) h(x) *$

	A+	A-	B+	B-	AB+	AB-	O+	O-
Observed Mean = Theor. Mean	2.0390	2.0441	2.0016	2.0362	2.0056	1.8253	2.0407	1.9999
Observed Variance	0.3156	0.2066	0.3676	0.2569	0.3577	0.1517	0.4589	0.4218
Theoretical Variance	0.5819	0.3759	0.6888	0.5013	0.4996	0.1608	0.6911	0.6450
K	.7833	.7685	.6581	.8098	.7587	.8000	.7206	.6773
P	.4538	.5396	.4988	.4566	.4943	.8700	.4661	.5001
Number of Observations	1462	178	624	28	188	23	1894	186
$D_{\max}$	.017	.005	.028	.015	.013	.006	.017	.024
Critical $D_{\max}$ $\alpha = .05$	.036	.102	.054	.242	.099	.280	.031	.100
Critical $D_{\max}$ $\alpha = .20$	.028	.080	.043	.190	.078	.210	.024	.079

* $g(x) = 1$ for $x = 2$, $g(x) = 0$ otherwise.
 $h(x) = p(1-p)^{x-1}$ for $x \geq 1$.

APPENDIX X

GENERATION OF EVENTS IN THE SIMULATOR

In a simulator it is necessary to generate the number of events of specified types and to generate the times at which these events occur. These events provide the occurrences upon which the logic of the simulator acts to represent what would happen if the events occurred in the real world situation. Thus, the events must be generated so that their occurrences in the simulator will be equivalent to the way they occur in the real world situation. Two different methods are used in the simulator to generate events. These methods, together with their advantages and disadvantages, are discussed in this appendix.

Experience Curve or Cumulative
Frequency Distribution Method

This method is applicable to all data generation situations, regardless of whether the data are continuous or discrete although it is particularly suited to the discrete case and will be discussed in that context since all the data required in the simulator were of that form. In order to use this method, it is necessary to have a frequency distribution which represents the desired relative frequencies for each possible value of the variable to be generated. This frequency distribution is usually obtained from data collected during the actual operation of the process being simulated, hence the name - experience curve. Starting with the observed relative frequencies:

$f(x_i)$ = the relative frequency of the i^{th} possible value of x

where $\sum f(x_i) = 1$

This relative frequency distribution is then represented as a cumulation relative frequency distribution of the form

$F(x_i)$ = the relative frequency of all value of $x \leq x_i$ or $F(x_i) = \sum f(x_i)$ for $x_i \leq x$.

In graphic form $F(x)$ can be shown as follows:

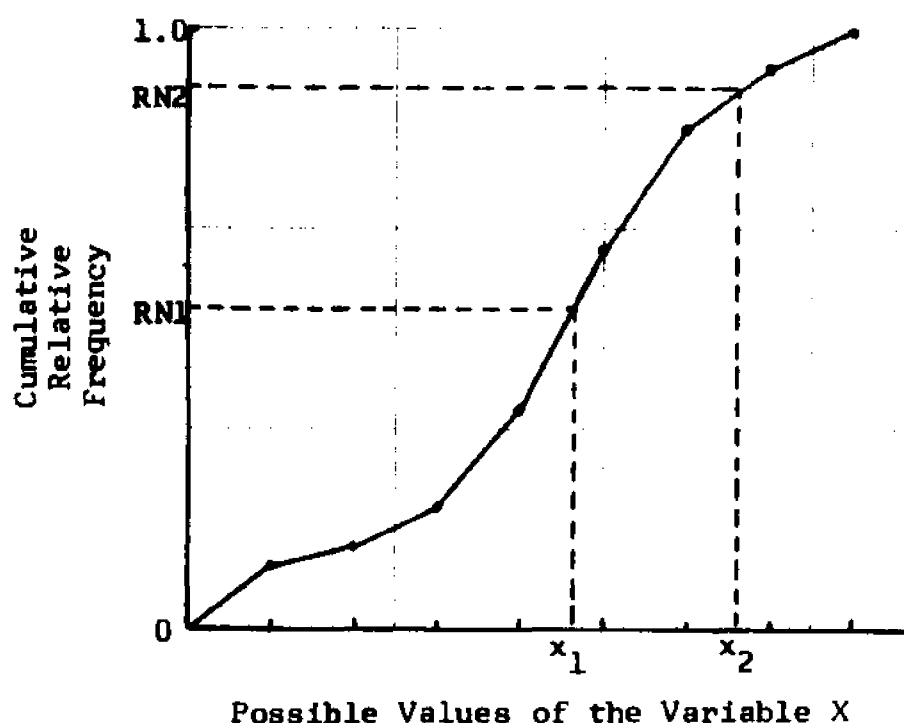


Fig. A10-1.--Use of an observed cumulative frequency distributed to generate random events.

The objective is to start with a random number (uniformly distributed over 0,1) and use that to represent a cumulative relative frequency and find that value of x which is appropriate for that particular cumulative relative frequency. The preceding figure illustrates two examples - if random number RN1 was generated, then the value of x would be x_1 , and similarly RN2 would

give rise to x_2 . This is accomplished by reading in the complete sequence of $F(x_i)$ into the computer (a value of $F(x_i)$ for each possible value of x_i) and storing them consecutively in memory. A uniform random number is generated using any one of the available generators¹ and the random number is compared to each cumulative frequency until the following condition is satisfied:

$$F(x_{i-1}) < \text{random number} \leq F(x_i)$$

then x_i is taken to be the randomly generated value. Since $F(x_i) - F(x_{i-1}) = f(x_i)$ and each uniformly generated random number is equally likely, then the probability that x will equal x_i , $P(x = x_i)$, will be exactly equal to $f(x_i)$ which is the desired relative frequency.

The computer logic to satisfy the condition stated above is iterative in nature and is best illustrated in the following flow chart.

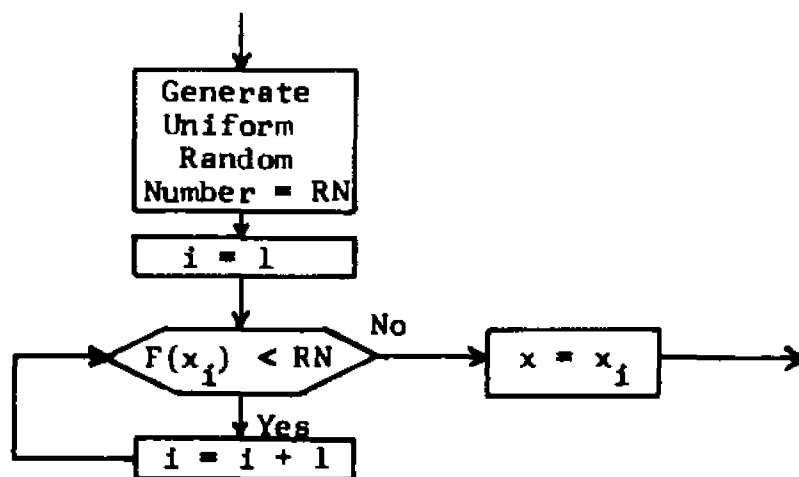


Fig. A10-2.--Flow chart for generating random events using a cumulative frequency distribution, $F(x)$.

¹The uniform random number generator used in the simulation program is based on the subroutine RANDU, listed in System/360 Scientific Subroutine Package (360A-CM-03X) Programmer's Manual, H20-0205, International Business Machines Corporation, White Plains, New York, 1966.

The method assigns to x the first value of x_i for which $F(x_i) \geq RN$, which satisfies the condition and guarantees frequencies in agreement with the relative frequency distribution used as input.

Use of a Theoretical Probability Distribution

If a theoretical probability distribution is used to describe the observed data, then it is possible to make use of the properties of this theoretical model in the generation of the random events described by the model. Several different methods are used, depending on the type of model, and some of the methods used are described here.

Simulation

If the probability model can be related to a real world analogue then the real situation can be simulated on a computer. The binomial probability distribution is such an example. This distribution can be represented as the distribution of the number of successes that are obtained from n independent tosses of a coin, where the probability of success on each trial is p . The computer generation of a random number of events which are known to have a binomial distribution with parameters n and p is accomplished by simulating n trials (generating n random numbers between 0 and 1) and counting the number of successes (the number of successes is equal to the number of random numbers which are less than p).

Relationship to another distribution

In some cases the probability model can be related to another model whose generation is easily accomplished. If, for

example, it is desired to generate Poisson arrivals, use can be made of the fact that when the number of arrivals per time period is Poisson then the times between these arrivals is exponentially distributed. Thus, if:

$$f(x) = e^{-u} u^x / x!$$

is the probability of x units arriving in a time period where u is the mean number of arrivals per period,

$$\text{then } g(y) = u e^{-uy}$$

is the probability of y time elapsing between a pair of arrivals where the mean time between arrivals = $1/u$.

Using the exponential cumulative distribution

$$G(y) = 1 - e^{-uy}$$

$$\text{and } 1-G(y) = e^{-uy}$$

$$\log [1-G(y)] = -uy$$

$$\log [1-G(y)] / -u = y$$

Thus, if the uniform random number is used to represent $1-G(y)$, then random times between arrivals can be easily generated by

$$y = \log (RN) / -u$$

These times between arrivals can be accumulated until an arrival is generated in the next time period. Then the number of arrivals in this time period is taken as the number of exponential times that were generated, minus the last one.

An alternative approach, again using the random number to represent $1-G(y)$, is to take the product of these random numbers as follows:

$$\begin{aligned}
 1-G(y) &= e^{-uy} = RN \\
 \prod_{i=1}^k (RN_i) &= \prod_{i=1}^k [1-G(y_i)] = \prod_{i=1}^k (e^{-uy_i}) \\
 &= e^{-u(y_1+y_2+\dots+y_k)}
 \end{aligned}$$

Since the objective is to generate the number of events in 1 period, we want to find the maximum value of k such that $\sum_{i=1}^k y_i$, the sum of the interarrival times, does not exceed 1.

Letting $\sum y_i \leq 1$ we have

$$\prod_{i=1}^k (RN_i) \geq e^{-u}$$

Then the number of arrivals in this period is taken as the number of random numbers generated before their product becomes smaller than e^{-u} .

Inverse of the cumulative distribution

In some cases, the cumulative distribution can be analytically expressed and the functional form can be solved for some value of the random variable. The geometric probability distribution represents an example of this type. If

$$f(x) = pq^{x-1}$$

where $p + q = 1$ and $f(x)$ is the probability of x events; $x = 1, 2, 3, \dots$

$$\begin{aligned}
 \text{then } F(x_i) &= \sum_{x \leq x_i} pq^{x-1} \\
 &= p(q^0 + q^1 + \dots + q^{x_i-1}) \\
 &= p(1 + q^1 + q^2 + \dots + q^{x_i-1})
 \end{aligned}$$

[Note: $1 + q + q^2 + \dots + q^{x_i-1}$ is a finite geometric series of x_i terms whose sum is $S_{x_i} = (1 - q^{x_i})/(1-q)$. Therefore,
 $F(x_i) = p(1 - q^{x_i})/(1-q)$]

Since $p + q = 1$, $p = 1 - q$

$$F(x_i) = 1 - q^{x_i}$$

$$q^{x_i} = 1 - F(x_i)$$

$$x_i \log q = \log [1 - F(x_i)]$$

$$x_i = \frac{\log [1 - F(x_i)]}{\log q}$$

Since an x is required such that

$$F(x-1) \leq RN < F(x)$$

or if $G(x) = 1 - F(x)$ then $G(x-1) \geq RN > G(x)$, then it is necessary to find the first integer value of x such that $G(x) \leq RN$.

$$\text{Since } x_0 = \left\lceil \frac{\log[1-F(x_i)]}{\log q} \right\rceil \leq \frac{\log[1-F(x_i)]}{\log q}$$

and the random number is used as $1-F(x_i)$ then $G(x_i)$ = the random number.

But $x_0 \leq x_i$, therefore $G(x_0) = 1 - F(x_0) \geq 1 - F(x_i)$, and $x_0 + 1$ will yield $G(x_0 + 1) < G(x_0)$

$$G(x_0 + 1) = 1 - F(x_0 + 1) < RN \text{ since } x_0 + 1 > x_i.$$

Thus, $G(x_0) \geq RN > G(x_0 + 1)$, which satisfies the above condition, and $x_0 + 1$ is the first integer value of x such that $G(x) \leq RN$ and therefore represents the randomly generated number.

Comparison Between Use of an Experience Curve and a Theoretical Probability Model

Applicability

The experience curve method is a much more general method of generating random events, since it can be used to describe any

set of observed data no matter how ill-behaved. The use of a theoretical probability distribution, however, requires that a model be found that is appropriate to the situation and that parameters for the model can be obtained. If the model is then amenable to one of the methods previously described, it can be used to generate the events.

Input and storage requirements

If the experience curve method is used, then it is necessary to read into the computer and provide storage in memory for each point on the cumulative distribution corresponding to a possible value of the random variable. Thus, if x could take on integer values between 0 and 21 it would be necessary to read in and store 22 values on the cumulative distribution. On the other hand, if a probability model with one or two parameters is used then it is only necessary to read in and store the one or two values of the parameters. Thus, the experience curve method requires a great deal more input preparation and a great deal more storage requirements than the use of a probability model and if many data sets have to be generated the total requirements may be prohibitive.

Generalization for research

One of the major functions of the simulator is to provide a research tool to investigate various changes in policies and/or various changes in exogenous variables, i.e., the input to the simulator. In addition, it is desired that the tool be available to other researchers to use in other environments which require

different inputs. If a statistical model has been used to describe the input generation then it is highly likely that the same model will still be appropriate but perhaps with different parameters. Then only one or two values will have to be changed for each data set for the models used in other situations. However, if an experience curve has been used it will require that enough data be collected to establish a new experience curve and the entire set of new cumulative points will have to be changed to run the simulator with the data appropriate to the new situation.

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