AN EXTREMAL PROPERTY OF THE FIFO DISCIPLINE
VIA AN ORDINAL VERSION OF $L = \lambda W$

Shlomo Halifin
Bell Communications Research
Morristown, NJ 07960

Ward Whitt
AT&T Bell Laboratories
Murray Hill, New Jersey 07974

ABSTRACT

We apply the relation $L = \lambda W$ to prove that in great generality the long-run average number of customers in a queueing system at an arrival epoch is equal to the long-run average number of arrivals during the period a customer spends in the system. This relation can be regarded as an ordinal version of $L = \lambda W$, arising when we measure time solely in terms of the number of arrivals that occur. We apply the ordinal version of $L = \lambda W$ to obtain a conservation law for single-server queues. We use this conservation law to establish an extremal property for the FIFO service discipline: We show that in a G/G/1 system the FIFO discipline minimizes (maximizes) the long-run average sojourn time per customer among all work-conserving disciplines that are non-anticipating with respect to the service times (may depend on completed service times, but not remaining service times) when the service-time distribution is NBUE (NWUE). Among the disciplines in this class are round robin, processor sharing and shortest expected remaining processing time.

Key Words: queues, conservation laws, Little's law, work-conserving service disciplines, stochastic comparisons, new better than used in expectation.

Copyright © 1989 by Marcel Dekker, Inc.
1. Introduction

In this paper we establish a conservation law that can be viewed as an ordinal version of the relation $L = \lambda W$, due to Little [10] and Stidham [14]. (We briefly review $L = \lambda W$ in Section 2.) Our main result, Theorem 2, states that in great generality (the same kind of conditions as for $L = \lambda W$) the long-run average number of customers in the system at an arrival epoch coincides with the long-run average number of arrivals during a customer's sojourn time (the interval between arrival and departure). We may either count or not count the arriving customer, but we do the same for both averages.

For the FIFO (first-in-first-out) discipline, our result is known, being any easy consequence of two facts. First, with the FIFO discipline, the customers left behind by a departing customer are just those customers that arrived during the departing customers sojourn time; see Keilson and Servi [9] for recent applications. Second, the departure-point averages coincide with the arrival-point averages, as can be seen from upcrossing and downcrossing arguments; e.g., see (9) below and p. 112 of Franken, König, Arndt and Schmidt [5]. However, we do not restrict attention to the FIFO discipline here.

We regard our conservation law as an ordinal version of $L = \lambda W$, because it is an analog of the standard version that arises when we do not measure or observe time. As with the standard version, customers are indexed in order of arrival, but we do not consider the actual arrival epochs. Similarly, customers depart some time after they arrive, but we do not consider the actual departure epochs. Instead, we measure time in terms of the arrival indices, so that the waiting time is replaced by the number of arrivals during a customer's sojourn time. In Section 3 we show that the ordinal version of $L = \lambda W$ can be derived from the standard version simply by making this interpretation.

In Section 4 we apply this ordinal version of $L = \lambda W$ to obtain a conservation law for single-server queues; see (6)-(10). In Section 5, we apply this conservation law to establish some useful comparisons between congestion
measures with different service disciplines. Theorem 3 shows that the FIFO
discipline minimizes (maximized) the expected sojourn time per customer in a
G/GI/1 model, among all work-conserving disciplines that are non-anticipating
with respect to the service times, when the service-time distribution is NBUE
(NWUE), i.e., new better (worse) than used in expectation. In this model, the
service times are i.i.d. (independent and identically distributed) and independent
of the arrival process, but the arrival process can be general, e.g., non-renewal.
Work-conserving means, first, that the server works at unit rate whenever there
is work to do, second, that the discipline does not affect the arrival times
and service requirements; see p. 418 of Heyman and Sobel [8]. Since the
discipline can affect the number of customers in the system, we cannot have a
limited number of queue positions; the discipline could then affect the arrivals
(customers that enter). On the other hand, we could have a finite capacity for
work (service time), because the workload process is independent of the
discipline within this class. Non-anticipating with respect to the service times
means that the discipline can depend on the amount of completed service time
of each customer, but not on the remaining service time. All work-conserving
disciplines are of this form when the service requirements are not known upon
arrival, but instead are only realized through service. Work-conserving
disciplines such as round robin (RR) and processor sharing (PS) that do not
depend on the service times in any way are of course included. A discipline
that uses the completed service times is shortest expected remaining processing
time (SERPT), where we compute the expectation conditional on the completed
service time of each customer and we use processor sharing when there are
ties. One might conjecture that SERPT always minimizes the long-run average
sojourn time within this class of disciplines; this is so for NBUE service-time
distributions, but not in general, even with a Poisson arrival process; see
Remark 5.5.

Of course, disciplines such as last-in first-out (LIFO) and random order
of service (ROS) for which the distribution of the equilibrium number of
customers in the system is the same as for FIFO have the same expected
sojourn time as FIFO (by virtue of $L = \lambda W$). A useful comparison with FIFO is
established for preemptive service-sharing disciplines such as RR, PS and SERPT. Consistent with intuition, FIFO tends to be good for low-variability service-time distributions, but bad for high-variability service-time distributions. With FIFO, more customers suffer from the exceptionally long service times. Since the exponential distribution is both NBUE and NWUE, the expected sojourn time is independent of the discipline in this class when the service-time distribution is exponential.

The stochastic comparisons under NBUE and NWUE conditions here extend previous results by Yamazaki and Sakasegawa for the special case of a GI/GI/1 queue (renewal arrival process) with a PS discipline having a finite number of service positions. Such systems were also analyzed by Rege and Sengupta [12] and Avi-Itzhak and Halfin [2]-[4].

2. Review of \( L = \lambda W \)

The standard \( L = \lambda W \) framework is a sequence of ordered pairs of random variables \( \{ (A_k, D_k) : k = 1, 2, ..., \} \), where \( 0 \leq A_k \leq A_{k+1} \) and \( A_k \leq D_k \) for all \( k \); see Stidham [14], [15] and Glynn and Whitt [6], [7]. We usually interpret \( A_k \) and \( D_k \) as the arrival and departure epochs of customer \( k \), but this is not necessary. Indeed, we will propose something different in the proof of Theorem 2.

Related quantities of interest are defined in terms of an indicator variable \( I_k(t) \), which is 1 if \( A_k \leq t \leq L_k \) and 0 otherwise. The number of customers in the system at time \( t \) and the waiting time of the \( k \)th customer are

\[
N(t) = \sum_{k=1}^{\infty} I_k(t), \quad t \geq 0, \quad \text{and} \quad W_k = D_k - A_k = \int_0^1 I_k(t) \, dt, \quad k \geq 1. \quad (1)
\]

We can now state a version of Little's law, \( L = \lambda W \); e.g., see Theorem 2 of Glynn and Whitt [6]. Throughout this paper, limits are understood to be with probability one (w.p.1).

**Theorem 1.** (Little's Law). Assume that \( k^{-1} A_k \to \lambda^{-1} \) as \( k \to \infty \), where \( 0 < \lambda < \infty \). Then the following are equivalent:

---

518  

HALPIN AND WHITTY  

THEOREM 1. (Little's Law). Assume that \( k^{-1} A_k \to \lambda^{-1} \) as \( k \to \infty \), where \( 0 < \lambda < \infty \). Then the following are equivalent:
(i) \( k^{-1} \sum_{j=1}^{k} W_j \rightarrow w \) as \( k \rightarrow \infty \)

(ii) \( t^{-1} \int_{0}^{t} N(t)dt \rightarrow \lambda w \) as \( t \rightarrow \infty \) and \( k^{-1} W_k \rightarrow 0 \) as \( k \rightarrow \infty \).

3. The Ordinal Version of \( L = \lambda W \)

We now cease to keep track of time. Instead, we measure time in terms of arrival indices, so that the waiting time becomes the number of arrivals during a customer's sojourn time. As in Section 2, we assume that the customers are totally ordered, but we allow multiple arrivals at the same time: i.e., the \( k^{th} \) customer has arrival epoch \( A_k \) with \( A_k \leq A_{k+1} \). In the framework of Section 2, let \( X_k \) be the number of customers with indices greater than \( k \) that arrive while customer \( k \) is in the system, and let \( N_k^w \) be the number of customers with indices less than \( k \) that are in the system at the arrival epoch of customer \( k \). (The qualification on the indices is included to cope with multiple events occurring at the same time.)

Here is our ordinal version of \( L = \lambda W \).

**Theorem 2.** The following are equivalent:

(i) \( k^{-1} \sum_{j \in \mathbb{Z}} X_j \rightarrow x \) as \( k \rightarrow \infty \);

(ii) \( k^{-1} \sum_{j=1}^{k} N_j^w \rightarrow x \) and \( k^{-1} X_k \rightarrow 0 \) as \( k \rightarrow \infty \).

A direct proof of Theorem 2 is not difficult (see Remark 3.1 below), but it essentially amounts to reproving a variant of Theorem 1. To see the connection to Theorem 1, we directly apply Theorem 1.

**Proof.** We put this problem in the framework of Section 2 by letting \( A_k = k \) and letting \( D_k \) be the index of the last arrival during customer \( k \)'s sojourn time (which is taken to be \( k \) if there are no other arrivals during this time). Then
\[ W_k = D_k - A_k = X_t \text{ is the number of arrivals with indices greater than } k \text{ during the sojourn time of customer } k. \] For \( t \) not an integer, \( N(t) \) defined by (1) is the number of customers in the system at arrival epoch \( \lfloor t \rfloor \) that are still present at arrival epoch \( \lfloor t \rfloor + 1 \), where \( \lfloor t \rfloor \) is the integer part of \( t \). Thus, \( N(t) \) only counts arrivals before \( \lfloor t \rfloor + 1 \). Consequently, for any integer \( k \),

\[
k^{-1} \int_{0}^{k} N(s) ds = k^{-1} \sum_{j=1}^{k} N_j^k,
\]

i.e., the average number of customers with smaller indices in the system upon arrival.

We are now ready to apply Theorem 1. Since \( A_k = k \), the initial assumption is trivially satisfied with \( \lambda = 1 \). Obviously, \( k^{-1} \int_{0}^{k} N(s) ds \to x \) as \( k \to \infty \) for integers \( k \) if and only if \( t^{-1} \int_{0}^{t} N(s) ds \to x \) as \( t \to \infty \), so

\[
t^{-1} \int_{0}^{t} N(s) ds \to x \text{ as } t \to \infty \text{ is equivalent to } k^{-1} \sum_{j=1}^{k} N_j^k \to x \text{ as } k \to \infty.
\]

Thus, Theorem 1 produces Theorem 2 with this interpretation. \( \square \)

Remarks. (3.1) A direct proof starts by letting \( Y_{ij} = 1 \) if \( j > i \) and customer \( j \) arrives while customer \( i \) is still in the system. Then let

\[
X_k = \sum_{j=1}^{\infty} Y_{ij} = \sum_{j=k+1}^{\infty} Y_{ij} \quad \text{and} \quad N_j^k = \sum_{i=1}^{\infty} Y_{ik} = \sum_{i=1}^{k} Y_{ik}.
\]

(3.2) Theorem 2 can also be proved by applying the general version of \( L = \lambda \hat{W} \) in Glynn and Whitt [7], but \( \xi \) is not any easier. In that context, Theorem 2 is interesting because it is treated by a two-dimensional cumulative input function \( F(s, t) \) generated by a double sum.

(3.3) A central-limit-theorem version of Theorem 2 can be established, just as the central-limit-theorem version of Theorem 1 in Glynn and Whitt [6].
4. Relations for a Single-Server Queue

Consider a single-server queueing system in which work is processed at unit rate whenever work is present and the server is working. We can trivially express the time spent in the system by customer \( k \), say \( T_k \), in terms of five components:

- \( S_k \) - service time of customer \( k \),
- \( W^k_\text{in} \) - work in system (in service time) just prior to arrival of customer \( k \),
- \( W^k_\text{arr} \) - work (in service time) to arrive during customer \( k \)'s sojourn time,
- \( I_k \) - idle time of the server during customer \( k \)'s sojourn time,
- \( W^k_\text{out} \) - work (in service time) just after the departure of customer \( k \).

For each \( k \geq 1 \),

\[
T_k = S_k + W^k_\text{in} + W^k_\text{arr} + I_k - W^k_\text{out}.
\]  

(5)

We can obtain corresponding relations among long-run averages and expected steady-state values. In particular, we consider expected steady-state values, i.e., in a stationary process framework, as in Franklin et al. [5]. Henceforth, assume that there is appropriate ergodicity as well as stationarity so that all long-run averages exist and coincide with expected stationary values. For the quantities in (5), this means the customer-stationary or synchronous version (Palm distribution). After dropping the index \( k \), we obtain

\[
E(T) = E(S) + E(W^\infty) + E(W^\text{arr}) + E(I) - E(W^\text{out}).
\]  

(6)

Furthermore, if the service times are i.i.d. and independent of the arrival process (a \( G/G/1 \) model), then we can express \( E(W^\infty) \) as

\[
E(W^\infty) = E(X)E(S),
\]  

(7)

where \( X \) is the stationary number of arrivals during a customer’s sojourn time. We can then apply Theorem 2 to obtain

\[
E(X) = E(N^\infty),
\]  

(8)

where \( N^\infty \) is the stationary number of customers in the system just prior to an arrival. We also have
\[ \mathcal{E}(N^d) = E(N^d), \quad (9) \]

where \( N^d \) is the stationary number of customers in the system just after a departure. (However, we must be careful about ties. For example, (9) is valid if we stipulate that \( N^d \) counts all customers that arrive at epoch \( A_k \) and have arrival indices less than \( k \), while \( N^d \) counts all customers that depart at epoch \( D_k \) and have arrival indices greater than \( k \). Then (9) follows by relating the upcrossings to the downcrossings.)

Finally, we can obtain an expression for \( E(N) \), where \( N \) is the time-stationary number of customers in the system at an arbitrary time and \( \lambda \) is the arrival rate (assumed to be well defined, with \( 0 < \lambda < \infty \)). From Theorem 1,

\[ E(N) = \lambda E(T). \quad (10) \]

5. Work-Conserving Disciplines Non-Anticipating with Respect to the Service Times

Now we assume that the GI/GI/1 queue of Section 4 has a work-conserving discipline; i.e., the server is never idle when a customer is in the system, and the discipline does not affect the arrival epochs or the amount of service given to any customer. Hence, \( I_k = 0 \) for all \( k \) in (5). As usual, let the traffic intensity be \( \rho = \lambda E(S) < 1 \). Under all the assumptions above,

\[ E(T) = E(S) + E(W^d) + E(W^d) - E(W^d) \]
\[ = ES + E(W^d) + E(N^d)E(S) - E(W^d) \]
\[ = ES + E(W^d) + [E(N^d)E(S) - E(W^d)]. \quad (11) \]

Of course, if the discipline is FIFO, then \( E(T) = E(S) + E(W^d) \) and \( W^d \) is distributed as the random sum of \( N^d \) i.i.d. *all* service times, so that

\[ E(W^d) = E(N^d)E(S). \quad (12) \]

Otherwise \( W^d \) is the sum of \( N^d \) residual service times, which can be quite complicated. However, we can use (11) to obtain useful comparisons for work-conserving disciplines that are non-anticipating with respect to the service
times. In particular, we can establish inequalities with NBUE and NWUE (new better or worse than used) service-time distributions. Recall that a service time $S$ is NBUE (NWUE) if

$$E(S-t \mid S>t) \leq (\geq) E(S)$$

for all $t$; (13)

e.g., see Stoyan [16]. We summarize the conclusions in the following theorem.

Theorem 3. (a) If the $GI/GI/1$ queue of Section 4 has a work-conserving discipline, then

$$E(T) = E(T; \text{FIFO}) + [E(N^d)E(S) - E(W^d)].$$

(b) If, in addition, the discipline is non-anticipating with respect to the service times, then

$$E(T) \leq (\geq) E(T; \text{FIFO}) \quad \text{and} \quad E(N) \leq (\geq) E(N; \text{FIFO})$$

(15)

whenever the service-time distribution is NWUE (NBUE), with equality holding when the service-time distribution is exponential.

Proof. (a) Apply (11) and (12). (b) Note that $W^d$ is the sum of $N^d$ residual service times, say $S_i^r$. Let $H^d$ represent the history of the system at the departure epoch associated with $N^d$ and $W^d$, which includes the completed service times of all customers in the system. Under NBUE

$$E(W^d) = E\left[\sum_{i=1}^{N^d} S_i^r \right] = E\left[\sum_{i=1}^{N^d} S_i^r \mid H^d\right]$$

$$\leq E\left[\sum_{i=1}^{N^d} (ES) \mid H^d\right] = E(N^d)E(S).$$

Remarks. (5.1) For the special case of a renewal arrival process, exponential service times and a PS discipline (the GI/M/1/∞PS model), Theorem 3(b) is covered by Theorem 2 of Ramaswami [11]. Note that Ramaswami's result shows for the special case of exponential service times that, although the first moment of $T$ does not depend on the discipline, the second moment (and thus the full distribution) of $T$ does depend on the discipline.
For GI/M/1, GI/E_2/1 and GI/D/1 queues, stronger stochastic comparisons consistent with Theorem 3(b) have been established in Section 3 of Shanthikumar and Sumita [13].

(5.3) For the special case of a Poisson arrival process and a PS discipline, Theorem 3(b) is an elementary consequence of known results; i.e.,

\[ E(T; M/G/1; PS) = E(T; M/M/1; FIFO) \]

(16)

For queues with common \( \rho \),

\[ E(T; M/M/1, FIFO) \leq (\geq) E(T; M/G/1, FIFO) \]

whenever \( c^2 \geq (\leq) 1 \), where \( c^2 \) is the squared coefficient of variation of the service-time distribution. It is well known that $N$ NBUE (NWUE) implies that \( c^2 \leq 1 (\geq 1) \).

(5.4) It is not difficult to see that the NBUE (NWUE) condition in Theorem 3(b) cannot be replaced by \( c^2 \leq 1 (\geq 1) \) for general GI/GI/1 systems (non-Poisson arrival processes). A proof can be obtained by using a light-traffic argument as in Whitt [17] with a batch Poisson arrival process with geometric batch sizes, which is a renewal process. By making the Poisson arrival rate small, almost all busy periods consist of a single batch. By making the mean batch size small, batch sizes of size greater than \( k \) are asymptotically negligible compared to batch sizes of size \( k \). All disciplines are the same for batches of size 1, so it suffices to consider batches of size 2. Let \( S_1 \) and \( S_2 \) be the service times of the two customers in such a batch. The expected sojourn time per customer during such a special busy period, say \( E(T^*) \), with FIFO is

\[ E(T^*; FIFO) = S_1 + S_2 / 2 \]

and, with PS, is

\[ E(T^*; PS) = \min\{S_1, S_2\} + \frac{\max\{S_1, S_2\} - \min\{S_1, S_2\}}{2} \]

By considering specific distributions for \( S_i \), e.g., two-point distributions, we see that \( c^2 = 1 \) is not the borderline between FIFO and PS.

(5.5) Note that FIFO coincides with SERPT for NBUE distributions and LERPT (longest) for NWUE distributions. Hence, Theorem 3(b) also
established extremal properties of SERPT and LERPT for subclasses of service-time distributions. However, it is not difficult to see that SERPT does not minimize $E(T)$ for all service-time distributions. For example, let $P(S=0)=0.9=1-P(S=11)$. Obviously, for $10 < r < 11$,

$$E(S-r | S > r) = 11 - r < 1.1 = E(S),$$

so that when a customer has been in the system for $t$ in this range, SERPT does not give a new arrival a negligible amount of service to see if the zero service time is realized, as it should. A formal proof can be developed by using Poisson arrivals and light traffic, as in [17]. □

We now apply PASTA (Poisson arrival processes see time averages) as in Wolff [18] to obtain another consequence of (11). For the external exogenous arrival process considered here, we automatically have Wolff's lack of anticipation assumption (LAA): For each $t$, $\{A(t+u) - A(u); u \geq 0\}$ is independent of $(N(s); 0 \leq s \leq t)$, where $A(t)$ is the arrival counting process.

**Theorem 4.** (a) In an M/GI/1∞ queue with a work-conserving discipline,

$$E(N^w) = E(N) = \frac{\rho}{1-\rho} \left[ 1 + \frac{E(W^a) - E(W^d)}{E(S)} \right]. \quad (17)$$

**Proof.** PASTA implies $E(N^w) = E(N)$ in (11). □

For an M/GI/1 model, we can also determine when $E(N)$ is the same as for an M/M/1 model with the FIFO discipline.

**Corollary.** In an M/GI/1∞ queue with a work-conserving discipline

$$E(N) = \frac{\rho}{1-\rho} = E(N; M/M/1, FIFO) \quad (18)$$

if and only if $E(W^a) = E(W^d)$.

**Remarks.** (5.6) In an M/GI/1 FIFO queue, $E(N^w)=E(N^d)$, but we typically do not have $E(W^a)=E(W^d)$, because $W^d$ is the sum of $N^d$ full service times, while $W^a$ is the sum of $N^a$ service times, one of which is residual (if $N^a \geq 1$).
(5.7) Let \( V \) be the steady-state workload at an arbitrary time. By PASTA, the distribution of \( W^a \) coincides with the distribution of \( V \) in the M/GI/1 model. Thus, \( E(W^a) = E(W^d) \) if and only if \( E(V) = E(W^d) \). Hence, departures see time averages (in the limited sense of these means) if and only if the moment \( E(N) \) satisfies (18).

6. A Heavy Traffic Limit and An Approximation

In this final section, we apply our results to the case of a GI/GI/1 queue with a discipline such that at most \( m \) customers in the system can have received partial service at any time. For this model let:

\[
N^d = N^d_x + N^d_y
\]

where \( N^d_x \) is the number of customers that have received partial service and \( N^d_y \) is the number of customers that have not received any service, among those \( N^d \) customers in the system at a departure epoch. Then

\[
E(N^d)E(S) - E(W^d) = E(N^d)E(S) - E(W^d), \tag{19}
\]

where \( W^d \) is the remaining work of the \( N^d \) customers that have received partial service.

For FIFO it is well known that

\[
\lim_{\rho \to 1} (1 - \rho)E(T) = E(S)(c_2^2 + c_1^2)/2, \tag{20}
\]

where \( c_2^2 \) and \( c_1^2 \) are the squared coefficients of variation of the interarrival times and service times, respectively; see p. 196 of Asmussen [1]. To relate our discipline to FIFO, we assume the following regularity condition:

\[
\sup_{\rho \geq 1} E(S > t | S > t) \leq K < \infty. \tag{21}
\]

Theorem 5. Consider a GI/GI/1 queue with a work-conserving discipline that is non-anticipating with respect to the service times and permits at most \( m \) customers in the system to have received partial service. If (21) holds, then

\[
\lim_{\rho \to 1} \frac{E(T)}{E(T; \text{ FIFO})} = 1.
\]
FIFO DISCIPLINE

Proof. By (14), (19) and (21),
\[ |E(T) - E(T; \text{FIFO})| = |E(N^2)E(S) - E(W^2)| \leq mK, \]
so that the conclusion follows from (20). □

From (14) and (19), it follows that if one has good estimates or approximations for \(E(N^2)\) and \(E(W^2)\), then one obtains good estimates or approximations for \(E(T) - E(T; \text{FIFO})\). For example, it should be much more efficient to estimate \(E(N^2)\) and \(E(W^2)\) by simulation than to estimate \(E(T) - E(T; \text{FIFO})\) directly by simulation, especially if \(p\) is near 1.

A specific example is an M/G/1 queue with \(m\) "service positions", where the customers occupying the service positions are served according to a processor-sharing discipline. Variants of this model have been considered by Avi-Itzhaki and Halfin [2] [4] and Yamazaki and Sakasegawa [19] [21]. In [2] the following approximation is proposed:

1. \(N^2\) is approximately distributed as \(\min(m-1, X)\); where \(X\) is the state of the equally loaded M/M/1 queue.

2. The amount of residual work of a customer in a service position at a departure is approximately distributed as the stationary excess or residual lifetime of the service time.

These approximations are exact for the extreme cases \(m=1\) and \(m=\infty\). The resulting approximation is
\[ E(T) = E(T; \text{FIFO}) + \frac{p-p^n}{1-p} \frac{1-c^2}{2} E(S). \] (22)

Approximation (22) and variations could be used more generally.

As noted in the introduction, Yamazaki and Sakasegawa [19] [21] derived for this model comparisons to the FIFO discipline. Their results are in agreement with the Theorem 3. Moreover, (22) is also proposed by them in (4.7) on p. 983 of [19].
ACKNOWLEDGMENTS

We thank Genji Yanazaki for bringing to our attention his related work in [19] and [21]. We thank Volker Schmidt and an anonymous referee for helpful comments.

REFERENCES


Shibam Halpin and Ward Whitt

An extremal property of the FIFO discipline via an ordinal version of $L = \lambda W$

Received: 6/1/1988

Revised: 2/25/1989

Accepted: 3/1/1989

Recommended by Soren Asmussen, Editor