Removal of microorganisms through slow sand filtration of chlorinated vs. nonchlorinated secondary effluents.

Syed Abdul Vakeel. Imran

Civil Engineering

1997

Abstract

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Removal of Microorganisms through Slow Sand Filtration of Chlorinated vs. Non-chlorinated Secondary Effluents

by

Syed Abdul Vakeel Imran

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

June, 1997

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This thesis, written by **Syed Abdul-Vakeel Imran** under the direction of his thesis adviser, and approved by his Thesis Committee has been presented to and accepted by the Dean of College of Graduate Studies in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

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To My Mother

ACKNOWLEDGEMENT

Praise and thanks be to ***Almighty Allah***, *the most Gracious, the most Merciful*, and Peace and Blessings of ***Almighty Allah*** be upon ***His Prophet*** (*SAW*). My thanks extend to my family and all my teachers and friends who helped me to shape my career and future.

In this regard my utmost thanks are to Dr. Shaukat Farooq, my thesis advisor, for being a guide and helping me across every hurdle, with his patience and cooperation. I also wish to thank my thesis committee members, Dr. Achi M. Ishaq, and Dr. M. S. Al-Suwaiyan, for their helpful suggestions which went a long way in helping me to accomplish this work.

I would also like to thank Mr. Abdul-Appa, and Mr. M. Essa for their time and effort.

Acknowledgement is due to the Civil Engineering Department of King Fahd University of Petroleum and Minerals (KFUPM) and King Abdul-Aziz City for Science and Technology (KACST), for the facilities and support provided for the completion of this research.

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THESIS ABSTRACT

NAME OF STUDENT	Syed Abdul-Vakeel Imran
TITLE OF STUDY	Removal of Microorganisms Through Slow Sand Filtration of Chlorinated vs. Nonchlorinated Secondary Effluents
MAJOR FIELD	Civil Engineering
DATE OF DEGREE	June, 1997

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MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia
June, 1997

ملخص البحث

الاسم الطالب : سيد عبد الوكيل عمران

مسمى البحث : التخلص عن الميكروبات في مياه المجاري المعالجة ثانويا بالكلور وذلك باستخدام المرشحات الرميلة البطيئة .

التخصيص : هندسة مدنية (مصادر المياه والبيئة)

تاريخ : يونيو ١٩٩٧ م .

يعد معدل فقدان الضغط فى المرشحات الرميلة البطيئة من أهم العوامل التى تؤخذ بالاعتبار عند تقييم مدى فعالية المرشحات الرميلة وخاصة عند استخدامها لمعالجة مياه الصرف المعالجه ثنائياً والتى عاده ماتكون غنية بالمواد المغذية للميكروبات .

أوضحت الأبحاث التجريبية السابقة وجود تعقيدات بسبب قصر المدة التى يمكن أثنائها استخدام هذه المرشحات وذلك بسبب ازدياد الطبقة السطحية (*Schmutzedecke*).

لحل مثل هذه المشاكل درست امكانية استخدام اضافة الكلور للمياه قبل ترشيحها . كان الغرض من هذا البحث الميدانى والذى استغرق حوالى السنة تقييم تأثير الكلور على ازالة الميكروبات من مياه الصرف الصحى المعالجة ثانوياً قبل ترشيحها . كانت النسب المؤية لإزالة المؤثرات الميكروبية الستة أثناء استخدام ثلاثة تراكيز للكلور (٠ ، ٥ ، ١٥ ملجم / ل)

٥، ٧٨ % ، ٦، ٨٩ % ، ٩٩،٩%بالنسبة للبليت كاونت ،٤، ٨٣ % ، ٢، ٩٨ % ، ٩ ، ٩٩ % بالنسبة للكوليفورم الإجمالى و ٨٦%،١، ٨٩ % ،٩٩،٩ % بالنسبة للكوليوفورم الفامط ، ٧٨ % ،٩٨،٥ % ،٢، ٩٩ % بالنسبة للكلوستريوم و ٨٠،١ % ،٩١،٣%، ٥، ٩٩% بالنسبة للكولفاج . بالنسبة لمعدل فقدان الضغط فى هذه المرشحات بعد ٥٣ يوماً من التشغيل فقد كان ٠ ، ٥٩ ، ٥ ، ٥ ، ٢٨ ، ٨،٦ بوصات على التوالى . تتبين من هذه الدراسة أن استخدام الكلور لمعالجة المياه قبل ترشيحها يقضى على زياده نمو البكتيريا فى الطبقة السطحية للمرشحات لما الحد الامثل الذى يعرقل ازالة الملونات ويقلل من معدل فقدان الضغط (*Schmutzedecke*) .

درجة الماجستير فى العلوم

جامعة الملك فهد للبترول والمعادن

الظهران _ المملكة العربية السعودية .

CHAPTER # 1

1. INTRODUCTION

Water has always been thought of as a low-cost abundant resource, but increasing population and standard of living emphasize a need for augmenting the available water resources. One way of augmenting the water resources is through water reuse. The potential of wastewater reuse for potable supply may be far-fetched but there is an increasing trend towards reuse for agricultural purposes, ground water recharge, landscape development, toilet flushing etc. Since human contact with this source of water is inevitable, there is an inherent danger in that the fecal-oral route is completed increasing the risk of transmission of water-borne diseases. The need of the hour is the development of efficient, economic and reliable processes that will effectively reduce the health risk due to water reuse. One such method is slow sand filtration.

Slow sand filtration has long been recognized as an economic and reliable treatment process for potable water treatment. Recent studies have

shown that it is equally reliable in the treatment of wastewater [Ellis, 1985; Farooq *et al.*,1993a; Farooq *et al.*,1993b]. Slow sand filters however have some inherent disadvantages like rapid headloss build-up, and time variant removal rates of microbial indicators due to filter ripening and uncontrolled growth of the *schmutzdecke* layer. A coordinated effort is required to develop and modify slow sand filters for its effective performance in the removal of microorganisms.

Pre-chlorination of the secondary effluent prior to filtration has been recommended as a measure to reduce headloss, achieve greater viral and bacterial removals, and reduce the fluctuations in the performance of the slow sand filter [Ives, 1971; Ellis,1985; Farooq and Imran, 1997a, 1997b].

A KACST funded project, involving a pilot-scale study under field conditions aimed at investigating the removal of microorganisms by slow sand filtration of secondary wastewater effluents, was undertaken at the Al-Khobar Sewage Treatment Plant. The proposed thesis work was conducted with the operation of the filter in order to generate detailed information about the effect of pre-chlorination on the performance of slow sand filters in the removal of indicator microorganisms. The indicator microorganisms studied were, standard plate count, total coliform, fecal coliform, fecal streptococcus, *Clostridium perfringens*, and coliphage.

CHAPTER # 2

2. LITERATURE REVIEW

2.1 Slow Sand Filters

In water treatment, slow sand filtration takes first place historically, as it was developed in the early 19th century for clarifying river waters [Ives, 1971]. Slow sand filtration was initially developed by John Gibb at Paisley in Scotland in 1804 to obtain pure water for his bleachery. His design was improved by Robert Thom working at Greenock in 1827 and was later employed by James Simpson at the Chelsea Water Company in 1829. Slow sand filters were commissioned at the Gorbel Sanitation and Water Company in 1846.

The Thames Water Authority in London employs slow sand filtration as the third stage in a four stage treatment process consisting of storage, rapid sand, slow sand filtration and disinfection [Ellis, 1984]

In the United States slow sand filtration has been effectively used to serve small communities of fewer than 10,000 persons for more than 50 years [Collins *et al.*, 1991]. The first municipal slow sand filter in the United States was built in Poughkeepsie near New York in 1872 [Logsdon and Fox, 1988]. There are about 47 full time slow sand filters with newer ones being installed frequently [Leland and Damewood III, 1990; Slezak and Sims, 1984].

Ellis [1984] has made an extensive review of the history, performance, influence of various physical, chemical and biological parameters, extent of research etc., on slow sand filters. He concluded that slow sand filters have all the advantages of being an efficient, economic and reliable water treatment process.

Bellamy *et al.* [1985], conducted experiments on six parallel pilot slow sand filters and observed the effect of temperature, sand bed depth, sand size, disinfection and biological activity on the treatment efficiency of slow sand filters. The study demonstrated increasing efficiency with increased temperatures, negligible effect of sand depth, increased efficiency with smaller sand size and increased microbial removals with greater biological activity. Bellamy observed that slow sand filters tended to act as black boxes, by reducing a varied influent microbial number, to within more or less constant effluent values.

Visscher [1990], studied the design, operation and maintenance of slow sand filtration and concluded that because of their simplicity, efficiency and

economy, slow sand filters are appropriate means of water treatment for community water supply in developing countries.

Cleasby *et al.* [1984] in an extensive study on the relative performance of slow sand and direct in-line filtration have shown that slow sand filtration outperformed in-line filtration on all important criteria including microbial removals.

Studies conducted by Wheeler *et al.* [1988], show that under normal circumstances, most of the activity of slow sand filters with respect to the removal of bacteria and viruses occur in the uppermost horizons of the filter where micro-fauna and flora are most abundant. Thus indicating that for microbial removal, it is in this area that both microbial predation and adsorption play an important role.

As the interest in slow sand filters is renewed there has been a lot of research into this area, especially in the developing countries. Much work has been carried out in assessing the existing slow sand filters and planning modifications and alterations for better quality control.

Pioneering work has been carried out at the Asian Institute of Technology (Thailand), University of Dar-Es-Salaam (Tanzania), University of Surrey (Peru), University of Loughborough (United Kingdom), King Fahd University of Petroleum and Minerals (Saudi Arabia), and the University of Zimbabwe (Zimbabwe).

2.2 Construction of Slow Sand Filters

A slow sand filter consists of a box constructed of reinforced concrete, ferro-cement and stone or brickwork masonry. The basic components of a slow sand filter are,

- a supernatant layer of raw water
- a bed of fine sand
- a system of underdrains
- an inlet and outlet structure
- a set of filter regulation and control devices

The supernatant water layer provides a head of water which is sufficient to drive the raw water through the bed of filter medium, while creating a detention period of several hours for the raw water. An outlet has to be provided to serve as an overflow for the supernatant water and to enable the removal of scum which may form on the water surface.

Sand is usually selected as the filter medium because it is economical, inert and durable. Filter sand should be free from clay, soil and organic matter.

The underdrain system provides an unobstructed passage of treated water and supports the bed of filter medium. Usually it consist of a main and lateral drain constructed from perforated pipes and covered with a layer of

graded gravel. This layer prevents the filter sand from entering or blocking the underdrains.

The flow is usually controlled by manipulating the outlet valve of the slow sand filter. This has to be done regularly to ensure that a constant flow is maintained in the system. Outlet-controlled flow is more efficient than inlet controlled flow as this allows a longer retention time for the supernatant water during the beginning of the filter run, resulting in improved efficiency.

The recommended level for the design criteria of slow sand filters as given by the IRC manual and the Ten States Standards given in Table 2.1.

Slow sand filter should be operated continuously because this requires less filter area and ensures a good quality effluent. Intermittent operations in which the filtration process is stopped at intervals should not be permitted as an unacceptable breakthrough of bacterial pollutants occurs four to five hours after filter recommences operation.

2.3 Mechanism of Slow Sand Filtration

In a slow sand filter the water percolates slowly through a porous sand bed. During this passage the physical and biological quality of the water improves considerably through a complex of biological, bio-chemical and physical processes. Table 2.2 gives the typical performance of conventional

Criterion	Ten State Standards	IRC Manual
Design Period	-	10-15 years
Period of Operation	-	24 hr/day
Filtration Rate	0.08-0.24 m/hr (0.03-0.10 gpm/sq ft)	0.1-0.2 m/hr (0.04-0.08 gpm/sq ft)
Height of Underdrains (Including Gravel)	-	0.3-0.5 m
Height of Supernatent Water	-	1 m
Number of Filter Bed Units	2 minimum	2 minimum
Filter Bed Depth	0.80 m (30 in)	0.50-0.90 m (18-35 in)
Filter Bed Area	-	5-200 m^2 per Filter
Sand Specification		
Effective Size	0.30-0.45 mm	0.15-0.30 mm
Uniformity Coefficient	≤ 2.5	< 3-5

Table 2.1: General Design Criteria for Slow Sand Filters

Water Quality Parameter	Treatment Performance
Turbidity	< 1.0 NTU
Coliforms	Reduced 1-3 log units
Enteric Viruses	Reduced 2-4 log units
Giardia cysts	Reduced 2-4 log units
Total Organic Carbon	< 15-25 %
Biodegradable Dissolved Organic Carbon	< 50 %
Trihalomethane Precursors	< 25 %

Table 2.2: Typical Treatment Performance of Conventional Slow Sand Filters [Collins et al., 1991]

slow sand filters in removing various pollutant parameters. In a mature sand bed a thin layer forms on the surface of the bed. This is also called as the '*schmutzedecke*' or dirty layer. This filter skin consists of retained organic and inorganic material and a great variety of biologically active micro-organisms which break down the organic matter. When after a period the filter skin gets clogged, the filtration capacity can be restored by cleaning the filter. This cleaning usually involves scraping off a top few centimeters of the filter bed [Duncan, 1988].

Huisman [1974], in his document prepared for the World Health Organization, presented a clear summary of the mode of action of a slow sand filter. He described the purification that begins while the water is above the sand. Here larger particles start to settle, smaller ones coalesce, and planktonic algae photosynthesize. The '*schmutzedecke*' layer which is slimy and gelatinous, comprising filamentatous algae, diatoms, and bacteria forms a major removal mechanism. Large particles of mineral and organic matter, living and dead algae, parasites, and a proportion of other impurities are left behind, trapped in the sticky mass, where they are broken down. Below the thin *schmutzedecke*, the water passes down through the bulk of the sand, taking one to two hours to pass through. Some straining takes place since most particles are smaller than the pores. Consequently, the sand grains become coated with a sticky layer of organic matter containing bacteriophages, and some predatory microbes such as protozoa and rotifers.

Organic matter is broken down and converted to cell material, and inoffensive inorganic materials are carried away in the now mineralized filtrate. This activity of the filter declines with the depth. Huisman advised against prechlorination or copper sulfate treatment before slow sand filtration, perhaps on the grounds that residuals of chlorine or copper could affect the biological activity in the filter. If the reservoir where the treatment takes place is reasonably remote from the filters, such toxic residuals however are unlikely to be significant.

2.4 Modifications to Enhance Slow Sand Filtration Efficiency

The past few decades have seen renewed interest in slow sand filtration for purposes other than potable water treatment. This has usually involved modifications to the conventional slow sand filters. Slow sand filters commissioned at different locations have varied removal efficiencies because of the difference in the water quality and the climatic conditions.

A number of modifications have been incorporated to overcome this variability in filter efficiency. These modifications may include the addition of pretreatment processes, changes to the design parameters or addition of chemicals or oxidants to enhance filter performance. Table 2.3 gives the modifications required for some of the recurrent problems in slow sand filters.

Concern	Modification
Increase raw water acceptability	Roughening filter, filter mats, settling, preozonation, prechlorination
Minimise filter-schmutzedecke cleaning, downtimes and ripening periods	Filter mats, filter-schmutzedecke harrowing, preozonation, prechlorination
Increased microbial removals	Preozonation, prechlorination

Table 2.3: Modifications to Enhance Treatment Performance of Slow Sand Filters Treating Secondary Effluents

Montiel *et al.*, [1988, 1989] have identified the different problems of filtration as related to the low turbidity removals, difficulty in the removal of certain inorganic and organic micro-pollutants, and excessive proliferation of algae in summer. The proposed modification alternatives included storage of raw water for 15 days, micro-straining, roughening filters, coagulation or pre-ozonation prior to filtration.

Wegelin [1988] has studied the potential of using horizontal roughening filters as a pretreatment process. This process removed most microorganisms in the size range of 0.5 to 60 um, after 30 days of filter operations. But the water quality within the first three days of filter operation was not comparable as most of the microorganisms passed through the roughening filter.

Ives and Rajapakse [1988], evaluated the use of pebble matrix filtration to reduce suspended solids in high turbidity waters. The pebble matrix filter consisted of a deep layer of pebbles, approximately 50mm in size, filled in between with sand less than 1 mm in size. This filter was reported to remove solids from values upto 5000mg/l to below 25 mg/l.

Greaves *et al.* [1988], have studied the potential of ozonation and subsequent slow sand filtration for the treatment of colored waters. The pilot plant investigation, revealed that preozonation achieved significant reduction in color, though the turbidity was not significantly reduced. Another observation in this study was the progressive rather than exponential development of headloss that gave extended runs.

Barrett and Silverstein [1988], studied the effects of high carbon loadings and high coliform counts in the influent on the performance of slow sand filters under tropical conditions. This bench scale study was conducted utilizing a 6 ppm glucose feed water at a temperature of 25 °C spiked with high densities of coliform bacteria. The results show a 80% reduction in the coliform counts. It was noted that due to the high influent numbers of coliforms the resultant effluent could not meet the safety standards.

Schellart [1988], explored the benefits of covered slow sand filtration. His observation revealed longer runs, less likelihood of fecal contamination by birds and filter animals, and a reduction in algal proliferation.

Baumann *et al.* [Ives, 1971] reported favorably using residual chlorine doses averaging 8.8 mg/l, but it appeared that this oxidized the organic and living matter on the sand surface.

2.5 Indicator Microorganisms

The actual enumeration of pathogenic microorganisms that are present in the wastewater effluents is untenable due to the practical difficulties involved in their culture and handling. Their numbers in wastewater effluents are very low making their enumeration a time-consuming and complicated process. Therefore to avoid the health risks posed by the handling of

microorganisms and to provide a reasonable estimate of their numbers, indicator microorganisms are used.

The indicator microorganisms can be termed as a specific or group of organisms that are similar in their survival characteristics as the pathogen and are present in sufficiently large numbers to facilitate their enumeration. The main requirements of an indicator however is that it should have a high positive correlation with the pathogen under study, and at all stages in its growth and decay it should maintain this correlation. Other requirements include ease of enumeration and non-pathogenecity. It is however interesting to note that due to the differences in the pathogen types, their modes of infection and their infective dose, it is difficult to obtain a universal indicator for all pathogens. The need becomes greater in the microbial characterization of wastewater treatment processes, because of the variability of incoming pathogens and their numbers.

Therefore it has been suggested by Berg that the best indicator of any pathogen is the pathogen itself. But this again is not possible due to the reasons mentioned above. The best indicator is the one whose densities correlate best with the health hazards associated with the given class of pollution source. The potential indicators must be screened with the following test before being used for correlation,

- must be consistently and exclusively associated with the source of the pathogens

- must be present in sufficient numbers to provide an accurate density estimate whenever the numbers of pathogens are such that the risk of illness is unacceptable
- should be as resistant to disinfection and environmental stresses, including toxic material, as the most resistant pathogen that may be present at significant levels in the source
- must be quantifiable by reasonably facile and inexpensive methods and with considerable accuracy, precision and specificity.

However a group of indicator microorganisms that are indicative of a wide range of the most common pathogens can be employed. The studies that found that the presence of pathogens in waters free from indicator organisms, strongly establish the fact that a single indicator is not a reliable mechanism of pathogen evaluation.

Therefore it has been suggested that for the complete microbial evaluation of the treatment facilities a group of indicators, of different type, be used [Berg, 1973].

2.5.1 Standard Plate Count

Standard Plate Counts provide an estimate of the density of aerobic and facultative aerobic heterotrophic bacteria in water. These are measured

as colony forming units/ml on Standard Methods Agar plate after 48 hr. in incubator at 35 °C as described in Standard Methods. Facilitates the collection of reliable data for water quality control measurements, especially for comparative and legal purposes.

2.5.2 Total Coliform

The total coliform group includes a broad spectrum of aerobic and facultative anaerobic, gram-negative, nonspore-forming bacilli that ferment lactose and produce gas within 48 hours at 35 °C. Some strains are widely distributed and are not specific to fecal material. *Aerobacter aerogenes* and *E. cloacae* are frequently found on various types of vegetation, in soil and in waters polluted some time in the past. Another coliform subgroup comprises of plant pathogens and other organisms of unknown taxonomy.

All these subgroups may however be found in sewage and polluted waters. Total coliforms have long been recognized as suitable microbiological indicators of water quality largely because they are easy to detect and quantify. It is estimated that the each person discharges an average of 1.95×10^9 coliforms per day. Field data from the Missouri river has indicated the virus to coliform ratio in surface waters to be 500000:1. This implies that for a 99.99% removal of viruses like hepatitis A, the corresponding coliform removals should be in the range of 99.9999%. However many field

investigations in polluted waters have revealed situations where total coliform measurements cannot always be equated to the input of fecal wastes. In these instances, the nutrients present in raw sewage discharges can contribute biodegradable products that support the regrowth of some strains, thereby increasing the coliform to virus ratio. Some strains of coliforms are found in the natural environment and are not specific to fecal pollution. This factor combined with others makes it difficult to utilize total coliform as a realistic indicator of fecal pollution.

2.5.3 Fecal Coliform

Fecal coliforms is a subgroup of the total coliform population, which corresponds more closely to the fecal contamination from warm blooded animals. In polluted waters, fecal coliform measurements relate more precisely to fecal contamination and are significantly less susceptible to bias caused by the regrowth characteristics of non-fecal coliforms.

About 93-98% of the total coliform group comprises of the fecal coliforms. However under excessive nutrient environments fecal coliforms too show a marked regrowth in polluted waters. Data analyzed from numerous polluted streams indicates that fecal coliforms do not survive in waters with a BOD of less than 30 mg/l. Enterovirus to fecal coliform ratio in sewage discharge is calculated at 1:100000.

2.5.4 Fecal Streptococcus

The occurrence of fecal streptococci in waters generally indicates fecal pollution. Although fecal streptococci rarely multiply in polluted waters, they may persist for extended periods in waters with a high electrolyte content and favorable temperatures. fecal streptococcus group includes a wide spectrum of strains that have specific fecal origins and diverse survival rates. The densities of this indicator group in polluted waters approach the magnitude observed for coliforms, or at times exceed it by a factor of 10, depending on the source of fecal pollution. The density difference between fecal coliforms and fecal streptococci in fecal material is a unique relationship that can be useful in defining sources of pollution. The fecal coliform to fecal streptococcus ratios in human feces and domestic wastes is greater than 4.0.

The advantages of fecal streptococci as pollution indicators arise from,

- Their occurrence in relatively high numbers in the excreta of humans and other warm-blooded animals
- Their presence in wastewaters and known polluted waters
- their absence from pure waters and environments having no contact with human and animal life
- Their persistence without multiplication outside the host body

- Their generally greater resistance to toxic chemical pollutants in certain waters

2.5.5 *Clostridium perfringens*

Clostridium perfringens is used as a supplemental indicator, in addition to routine microbial examinations of water and wastewaters. It is an obligate anaerobe belonging to the sulfite-reducing spore forming group. *Clostridium perfringens* is a spore former and since such organisms can generally persist longer in water than non-spore forming bacteria such as coliforms, it has been suggested that this anaerobe might be useful as an indicator of past pollution. This is usually done by comparing the *Clostridium perfringens* spores in a given sample with the unstressed recent vegetative cells. The vegetative cells are expected to predominate in the raw sewage. Spore development becomes responsive to the degree of sewage treatment, time and distance downstream from the point of discharge. Since bacterial spores are very resistant, *Clostridium perfringens* may also be used as an indicator of fecal pollution in waters receiving toxic industrial wastes that rapidly destroy other bacterial indicators. The methodology for the enumeration and detection of *Clostridium perfringens* is not complicated as it can tolerate upto 5% oxygen without significant loss of quantitative recovery. Where a rigorous test of sewage treatment is desired, including sewage control, a limit on *Clostridium*

perfringens densities in the discharge can prove more meaningful than the traditional coliform standards [Cabelli, 1978].

2.5.6 Coliphages

The somatic coliphages comprises of all tailed and cubic bacteriophages capable of infecting a wide range *E. coli* host strain by adsorption to receptors in the cell envelope. The somatic coliphage counts thus obtained may be more or less compared to coliphage counts reported in other literature [Havelaar and Nieuwstad,1985].

Kott *et al.* [1973], reported that the ratio of human enteric viruses to coliphages was $1:10^4$ in winter, summer and fall and $1:10^5$ in spring. The results of this study showed that coliphages were not inactivated by a chlorine dose of 20 mg/l. The need for more information on the inactivation of coliphages was stressed.

Slade [1981], studied the occurrence, survival and pathogenic potential of viruses in sewage. He concludes that though it is highly unlikely, almost any virus could get into wastewater and survive treatment with unknown epidemiological consequences and stresses the need for studies that will help in the design and installation of appropriate treatment processes.

Gerba et al, [1980], Glass and O'Brien [1980] and Gerba [1981], summarized the virus removal/inactivation in various wastewater treatment

processes that have been reported by various researchers. He had reported the enterovirus removal by slow sand filtration in the range of 10-90%, and recommends it as a tertiary treatment process for wastewater treatment.

The mechanisms of virus removal by various disinfection processes were studied by Mills [1975], Malina [1976] and Butler [1981]. They regarded conventional wastewater treatment processes as highly inefficient and stressed the need for tertiary treatment and disinfection as a means of a more comprehensive virus removal. Butler [1981], points out to the fact that treatment processes like slow sand filtration, although giving high virus removals defer the problem of virus disinfection to the sludge treatment.

After studying the distribution of various pathogens with reference to the presence of indicator organisms, Geldreich [1978] has concluded that the prerequisites for the ideal indicator for fecal contamination in water has restricted the probable candidates to total coliforms, fecal coliforms, fecal streptococci, and *Clostridium perfringens*.

Scarpino [1978], has concluded that the indigenous coliphages might be useful for evaluating the performances of wastewater treatment plants in removing animal viruses. And since the bacteriophages (primarily the coliphages) provide a sensitive, convenient, economic and reliable index of water contamination by enteric viruses and bacteria, they have been proposed as an indirect measure of enteric virus presence in water and wastewater.

In an epidemiological study aimed at evaluating the drinking water related health risks, Sobsey *et al.* [1993], have evaluated the conceptual framework of identifying the health risks related to microbial presence in drinking waters. The conceptual framework consisted of hazard identification, exposure assessment, effects assessment, risk assessment and characterization and risk management. The same conceptual framework can be applied effectively to water reuse [Asano and Sakaji, 1990].

In a study of the chlorination experiments on f2 and MS_2 coliphages, attenuated with Polio I strain, Kott *et al.* [1974], have reported that the coliphages were more resistant than the attenuated Polio I virus. This study establishes that bacteriophages, particularly coliphages can serve as viral pollution indicators in wastewater treatment.

A study conducted by Borrega *et al.* [1987] to test the feasibility of *E. coli* specific bacteriophages as universal fecal pollution indicators has indicated that coliphages are good indicators of the presence of pathogenic micro-organisms. It is claimed that coliphages performed better as indicators of fecal pollution than the classical indicator systems currently employed.

2.6 Removal of Indicator Micro-organisms Through Slow Sand Filtration

In a review of the removal of microbial indicators and viruses in slow sand filters Wheeler *et al.* [1988], have summarized the mechanisms and of removal and the extent of research into the microbial performance of slow sand filters. According to this review a the impacts of a number of water treatment processes were studied by Kool [1979]. Kool reported that slow sand filtration was capable of reducing the virus and enterovirus by 1-2 log units.

According to a review by Lloyd and Morris [1982], slow sand filtration was substantially more efficient than rapid sand filtration. Their studies achieved a poliovirus 1 reduction of 95-100% and a MS2 coliphage reduction by 99.75-99.996%.

Detailed work was conducted by Poynter and Slade [1977], over a period of years using perspex slow sand filter columns of surface area 0.09 m^2. At flow rates of 0.2-0.5 m/hr and water temperatures of 5-18 °C, reductions in bacteria and viruses were reported as follows: poliovirus 1: 98.25-99.99%, *E. coli*: 88.0-98.6%, and fecal (thermotolerant) fraction: 94.5-98.4%. Observations made during this study revealed that the virus removal is a biologically related phenomena with microbial predation and adsorption to biomass having the greatest contribution in the topmost *schmutzedecke* layer.

Another result based on the experiments conducted by McConnell *et al.* [1984], has found no significant difference between aged slow sand filters with and without an active viable *schmutzedecke*. Thus it was concluded that biological activity within the sand horizons was not primarily responsible for elimination of viruses. These results were not in agreement with the observations made by Poynter and Slade [1977]. It was concluded that although their relative importance may vary, adsorption to biological and non-biological surfaces plays an important role throughout the depth of the filter.

Results of work conducted by Wheeler *et al.* [1988], reveal a fecal streptococcus removal of 88% at a sand depth of 100 mm, 96% at depths of 200 mm, and 98% at depth of 500 mm.

The thermotolerant plate count removals were 74% at a depth of 500 mm, whereas the plate count removals were 85% at the same depth. An average bacteriophage removal of around 99.6% was observed.

Ellis [1985], conducted studies on bench scale slow sand filters. He observed that the slow sand filters gave consistent coliform removals greater than 95%. On the basis of his studies he recommended slow sand filters as a tertiary treatment process for municipal sewage.

Bellamy *et al.*, [1985], conducted studies on six pilot plants in which the process variables were varied. One run involved the chlorination of the schmutzedecke layer by maintaining a chlorine residual of 5 mg/l in the supernatant water. These studies showed reduced coliform and standard

plate count removals due to prechlorination as compared to the control filters. Bellamy explained this as a result of fairly constant effluent for varied influent quality.

Goldgrabe *et al.*, [1993], studied the development of headloss and particle removal in sand filters and granular activated carbon (GAC) filters. The effect of prechlorination was studied on the removal of total particle counts and the run length. It was found that prechlorinated filters gave 0.4-0.5 log better net removal than the nonchlorinated filters. Further it was observed that prechlorinated filters gave longer run times compared to chlorinated filters.

LeChevallier *et al.*,[1992], examined the application of biological treatment strategies for the current problems in water treatment. He reports that the application of free chlorine to biologically active GAC filters does not inhibit assimilable organic carbon (AOC) removals and that prechlorination resulted in significantly lower effluent AOC than preozonation. This study established the need for predisinfection in biologically active filters.

2.7 Slow Sand Filtration as Tertiary Treatment Process for Wastewater

The use of slow sand filters for treatment of secondary effluents is a recent concept that was examined and explored by Ellis [1985] in the mid

80's. Ellis found that results of previous studies on the viability of slow sand filtration as a tertiary treatment process gave a conservative picture of the treatment efficiency of slow sand filters. Studies using a slow sand filtration unit of 140 mm diameter perspex cylinder, 2.65m in height and 950mm sand depth of fine sand was used. The sand size was initially 0.3mm and later changed to 0.6mm. At treatment rates of 3.5 md^{-1} and 7.5 d^{-1} the slow sand filter was able to remove at least 90% of suspended solids, more than 65% of the remaining BOD and over 95% of the coliforms.

A comprehensive study on the effect of sand sizes and filter depths on the treatment efficiency of slow sand filters was conducted by Farooq *et al.* [1993a, 1993b]. The filter depths investigated were 135, 105, 55 cm and two sand sizes of 0.31 and 0.56 mm effective size. It was found that the removals of BOD, COD, standard plate counts, nitrate, phosphate, and sulfate vary from 79-92%, 40-60%, 88-93%, 17-30%, 8.3-84% and 5-10% respectively at various sand depths for two different sizes of sand. They concluded that the percent removals of different parameters investigated in the study decreased by decreasing the sand depth and/or by increasing the sand size. Therefore, it was suggested that sand of coarser size with deeper bed be used in contrast to finer sand of shallow bed in order to get desired efficiency.

A research project funded by King Abdul-Aziz City for Science and Technology (Riyadh) entitled "*Tertiary Treatment of Wastewater Effluents with Slow Sand Filtration for Removal of Viruses*", was conducted at the

Department of Civil Engineering, King Fahd University of Petroleum and Minerals (Dhahran). Some of the pertinent recommendations of this project were to use slow sand filter as a effluent polishing technique due to its observed efficiency in microbial removals.

Another recommendation of this study was the use of prechlorination of the secondary effluents as a means of reducing headloss and thereby achieving extended filter runs [Farooq and Nakhla, 1996].

2.8 Problems Associated with Slow Sand Filter as a Tertiary Treatment Process

There is a fundamental difference in the approach towards slow sand filters as a potable water treatment process and as a tertiary treatment process for wastewater. Though the mode of treatment remains essentially the same in both the processes, the differences arise due to the quality of water to be treated.

The influents to the potable water treatment are essentially low in microbial populations and have very little nutrients to nourish the microorganisms. This results in a fragile filter ecology. Any disturbance in this ecology is bound to reflect in the reduced efficiency of slow sand filters. In potable water treatment the main aim is to develop the *schmutzedecke* layer so as to achieve greater filter efficiency. Therefore any chemical additive that

interferes with the development of the *schmutzedecke* is treated with caution [Ellis, 1985]. Therefore the nourishment of the *schmutzedecke* layer becomes the primary objective for a potable water treatment utility.

Slow sand filters which treat the secondary effluents on the other hand, have influent rich in nutrients and microbial populations. There is also the added factor of suspended solids and turbidity that tends to accelerate the development of the *schmutzedecke* layer. This is reflected in the increased headloss in the filters, resulting in shorter filter runs. Algal proliferation of the filter beds is also a common problem encountered during the warmer season. The growth of algae in the filter gives rise to odor problems in the treated water along the choking of the filter bed leading to a drastic increase in headloss. Therefore the primary objective for the slow sand filter treating secondary wastewater effluents is to control the growth of the *schmutzedecke* layer. This has been achieved in a number of ways ranging from pre-filtration in roughening filters, covered slow sand filtration, pre-settling etc., Recent years have seen an increasing trend towards the use of pre-disinfection of the influent water to achieve more uniform treatment rates and to control the development of headloss [LeChevallier *et al.*,1992; Goldgrabe *et al.*,1993; Farooq and Imran,1997a, 1997b].

The development of headloss provides a useful indication of the health of the slow sand filter. An ideal case would be a static headloss at an optimum value. A rapid increase in headloss indicates the uncontrolled growth of the

schmutzedecke layer or an algal proliferation. A decrease in headloss, may mean scouring of the *schmutzedecke* or oxidation of filter bed. An optimum case would be a slow increase in headloss as this would result in longer filter runs and reduce the variability in the filtration efficiency. The headloss curve as obtained in bench scale studies approximates to an exponential curve. But pilot plant studies show a marked deviation from the exponential curve as the headloss is sensitive to changes in the influent turbidity and suspended solids.

2.9 Chlorine as a Disinfectant

Of the halogen disinfectants, chlorine has a long history as a successful disinfectant. Chlorine is a strong electrophilic oxidizing agent which can react with nucleic acids as well as proteins. The mechanism of its action in killing or inactivating microorganisms depends on several variables. The rate of diffusion into the cell and reaction with the cell components are important variables and depend on the physiological condition of an organism, the concentration and nature of the active chlorine, pH and temperature. Hypochlorous acid HOCl and Cl_2, the most active forms, can easily pass through cell membranes due to their small molecular size and electrical neutrality. In general descending order of disinfecting activity, the forms of active chlorine are chlorine gas, HOCl, OCl^-, dichloramine, monochloramine and organic chloramines. The existing concentrations of these species are

functions of pH and the concentration of ammonia containing compounds in the water. Organic chloramines and other organic chlorine containing reaction products have little or no microbial effect. Although inorganic chloramines are somewhat active against bacteria, they are relatively ineffective in virus inactivation.

This difference in the chlorine inactivation between bacteria and viruses may be explained by considering the possible mechanisms of inactivation. Bacterial respiration is believed to take place on the cell surface, with simple sugars and allied compounds on the outside of the cell wall and enzymes, co-enzymes and H-carriers on the inside. With these highly active systems present close to the cell wall, biocidal agents can react with H-carriers and co-enzymes, causing disruption of the respiratory process. Early studies involving chlorine reactions inside the cells suggested that bactericidal action resulted from inhibition of various sulfhydryl enzymes and other enzymes sensitive to oxidation. In studies with *E. coli*, inhibition of glucose oxidation was observed to parallel the percentage of bacteria killed. It was concluded that cell death resulted from inhibition of adolase and triosephosphate dehydrogenase, which are enzymes associated with glucose metabolism. Suppression of glutamate decaroxylase activity by chlorine was noted. More recently, chlorine has been found to affect infectious viral RNA and DNA as well as other protein components. Depending on the conditions of chlorination, protein reactions besides oxidation of sulhydryl groups may occur, including substitution on the

tyrosine and histidine rings, oxidation of tryptophan, and under strong acid conditions, cleavage of peptides. The greater resistance of certain enteric viruses to free chlorine over that of enteric viruses has been ascribed to the lack of enzymes and other sensitive systems associated with viruses.

Data on inactivation of viruses by heat and some chemical agents indicate that the inactivation involves denaturation of their protein capsids, with the nucleic acid core remaining unaffected. This inactivation may not necessarily insure complete destruction of the virus, because the nucleic acid is still infectious. Denaturation of nucleic material is more difficult to achieve than destruction of the sulfhydryl and H-carriers by oxidizing agents. The greater resistance of viruses to chlorine and other chemical agents may also be a function of target size, since bacteria are much larger than viruses and thus contain more critical size that is sensitive to oxidizing agents.

When chlorine is dissolved in water it hydrolyses to form hypohalous acids,

$$Cl_2 + H_2O \leftrightarrow HOCl + Cl^- + H^+$$

and the acid ionizes to form the hypohalite ion.

$$HOCl \leftrightarrow OCl^- + H^+$$

Hydrolysis and ionization are pH, temperature and concentration dependent. The hypohalous acid is the most active molecule. At low pH the chlorine molecule is predominant whereas above pH 9 the hypochlorite ion is

present. Chlorine functions best against viruses at about pH 6 when optimum levels of the acids are formed (the pH of many effluents is about 8).

The disinfection potential of chlorine against viruses has been demonstrated by various experimental model systems as well as in the field. Viruses range in their sensitivity, for instance a laboratory strain of coxsackie virus was the most resistant enterovirus tested. And some other enteroviruses like reovirus were more susceptible than any of the tested entero virus. Fresh isolates of the entero virus appear more resistant than laboratory adapted strains. Certain viruses may have resistance selectively induced by cultivation in the presence of chlorine. This observation raised objections to the inadequate chlorination because of the possibility that such resistant viruses may when released in the effluent ultimately replicate in susceptible people. The need for thorough mixing of disinfectant to ensure optimal activity is stressed especially when virus is adsorbed to particulate matter by which it is protected so that the design of an efficient chlorinating systems becomes important. Chlorine has some remarkably useful characteristics especially in water with slightly nitrogenous contamination when it forms stable, persistent and disinfecting mono, di and tri-chloramines.

$$HOCl + NH_3 \leftrightarrow NH_2Cl + H_2O$$

$$HOCl + NH_2 \leftrightarrow NHCl_2 + H_2O$$

$$HOCl + NHCl_2 \leftrightarrow NCl_3 + H_2O$$

These reactions are concentration dependent such that, when the ratio of chlorine to ammonia is greater than 20:1, free chlorine is again available for hydrolysis. This phenomenon is known as break-point chlorination. The mono and di-chloramines decompose to release nitrogen.

$$2\ NHCl_2 + HOCl \longrightarrow N_2 + 3\ HCl + H_2O$$

$$2\ NHCl_2 \longrightarrow N_2 + 2\ HCl + Cl_2$$

These are however less active against viruses than bacteria.

Sobsey *et al.* [1991] found that cell associated enteric viruses were more resistant to chlorination than the dispersed viruses. The results of experiments on the inactivation of dispersed and cell associated hepatitis A virus by a chlorine dose of 0.5 mg/l at a pH of 6.5 clearly indicate that cell associated HAV is ten fold more resistant than dispersed HAV.

Havelaar and Nieuwstad [1985] in a study on bacteriophages and fecal bacteria as indicators of chlorination efficiency has noted that the reduction of bacteriophages was not related to chlorine residual but instead to chlorine dose. The study established that to achieve a 3 log unit kill of bacteriophages a chlorine dose of 16 mg/l is necessary.

The fecal streptococci were found to be more resistant to chlorination than thermotolerant coliforms. The inactivation potential of fecal streptococci was found to be in between the coliforms and bacteriophages. Chlorine doses upto 5 mg/l did not reduce the Clostridia significantly.

2.10 Chlorination of Secondary Effluents Prior to Slow Sand Filtration

With increasing volumes of treated waste water being targeted for reuse there is a need to develop reliable methods to mitigate the health safety risk caused by bacterial and viral infection. There is an increased risk in allowing partially treated water for reuse, as this will lead to the re-circulation of pathogens and thereby creating more resistant strains. Thus making it imperative for a total and comprehensive microbial removal in wastewater treatment so that pathogens do not survive. Modifications and additions to existing treatment works for the complete removal of pathogens are the order of the day. Slow sand filters have long been plagued with uncontrollable headloss due to rapid build up of the *schmutzdecke* layer, thereby fluctuating the microbial removal rates. Pre-chlorination has been suggested as a way of solving this problem.

Ives [1971], points out the difficulties in water treatment by slow sand filtration such as the intermittent draining down of the filter during its run to slow down algal blooms on the *schmutzedecke*, overdevelopment of the blanket weed (Cladophora) on the surface, the growth of certain organisms like Nais worm in the underdrains and production of hydrogen sulfide due to warm weather anaerobiosis in the sand layers which reduced sulfates in the water. Prechlorination ranks among the various modifications that Ives suggests for the improvement of slow sand filters.

Based on the results of a one year study on pilot slow sand filters, Farooq and Imran [1997a,1997b], have recommended the use of prechlorination of secondary effluents prior to slow sand filtration. The microbial removals in the prechlorinated filters were found to be better and more consistent than the nonchlorinated slow sand filters. The run length of the chlorinated filter was greater than 100 days compared to 48 days for the nonchlorinated filters.

CHAPTER # 3

3. OBJECTIVES OF THE STUDY

The objectives of this study are to investigate and monitor the removal of bacterial and viral indicator microorganisms through slow sand filters under two different prechlorination doses on a pilot plant under field conditions. To get a clearer picture of the microbial removals due to the different treatment levels namely, chlorination, control slow sand filtration and test filtration that incorporates the combined effects of chlorination and subsequent filtration were studied. Six different microbial parameters were selected because they are widely recommended as indicators of pathogens in waters and wastewater. These are standard plate counts, total coliforms, fecal coliforms, fecal streptococcus, *Clostridium perfringens*, and coliphages.

The specific objectives can be summarized as:

1. To determine the removal of bacterial and viral indicator microorganisms by slow sand filtration of secondary effluents.

2. To determine the removal of bacterial and viral indicator microorganisms at two chlorine dosages of 5 mg/l and 15 mg/l.

3. To determine the removal of bacterial and viral indicator microorganisms due to chlorination and subsequent slow sand filtration of the secondary wastewater effluents.

4. To compare the effect of prechlorination on the removal efficiency of indicator microorganisms in slow sand filters.

5. To examine the effect of prechlorination on the headloss development in slow sand filters

To examine the effect of chlorination on the microbial removal efficiencies in the slow sand filters it was decided to use two chlorine dosages. A conservative dose of 5mg/l was applied in the first phase and a higher dose of 15 mg/l was utilized in the second phase. These doses were selected on the basis of those found in literature for nutrient rich and high coliform surface waters. Table 3.1 gives the prechlorination dosages in various research studies for the control of headloss.

Table 3.1: Recommended Prechlorination Dosages for the Control of Microorganisms and Headloss

Studied By	**Chlorine Dose**	**Observations**
Farooq and Imran (1997)	5.0 & 15.0 mg/l	Improved filter runs and microbial removals
Goldgrabe et al (1991)	3.25 mg/l	Decreased headloss, increased TPC removal by 0.5 log units
Lechevallier et al (1990)	5.0 mg/l	Increase the efficiency of biologically active rapid filters
Ellis (1985)	0.2 - 1.0 mg/l	Prevent algal blooms
Ives (1977)	8.8 mg/l	Improved filter runs, better microbial removals

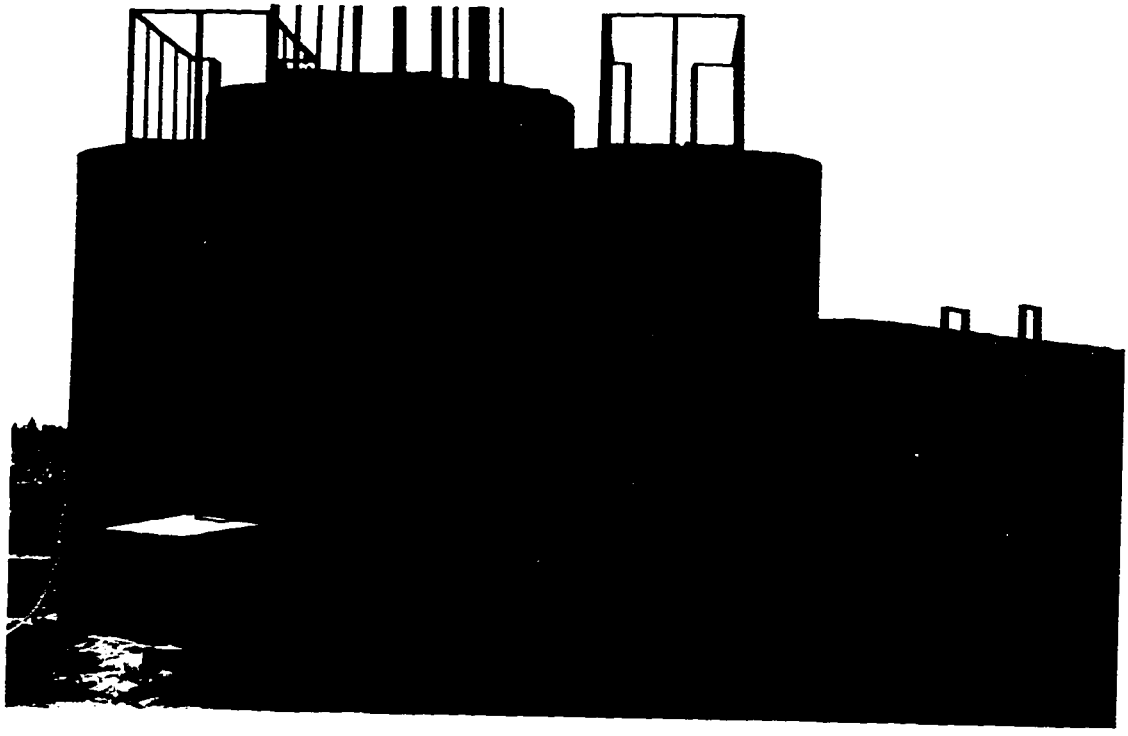
CHAPTER #4

4. MATERIALS AND METHODS

4.1 Experimental Setup

Two modular slow sand filters, one settling tank and one chlorination tank were constructed in the field at the Al-Khobar Sewage Treatment Plant. These were constructed on a 15m x 15m plot bordered in the east by the secondary clarifiers to facilitate the conveyance of unchlorinated secondary effluent to the settling tank. The layout of the pilot slow sand filters at the treatment plant is given in Fig 4.1.Their schematic layout is shown in Fig 4.2.

Fig 4.1: Layout of Pilot Slow Sand Filter Plant at the Al-Khobar Sewage Treatment Plant



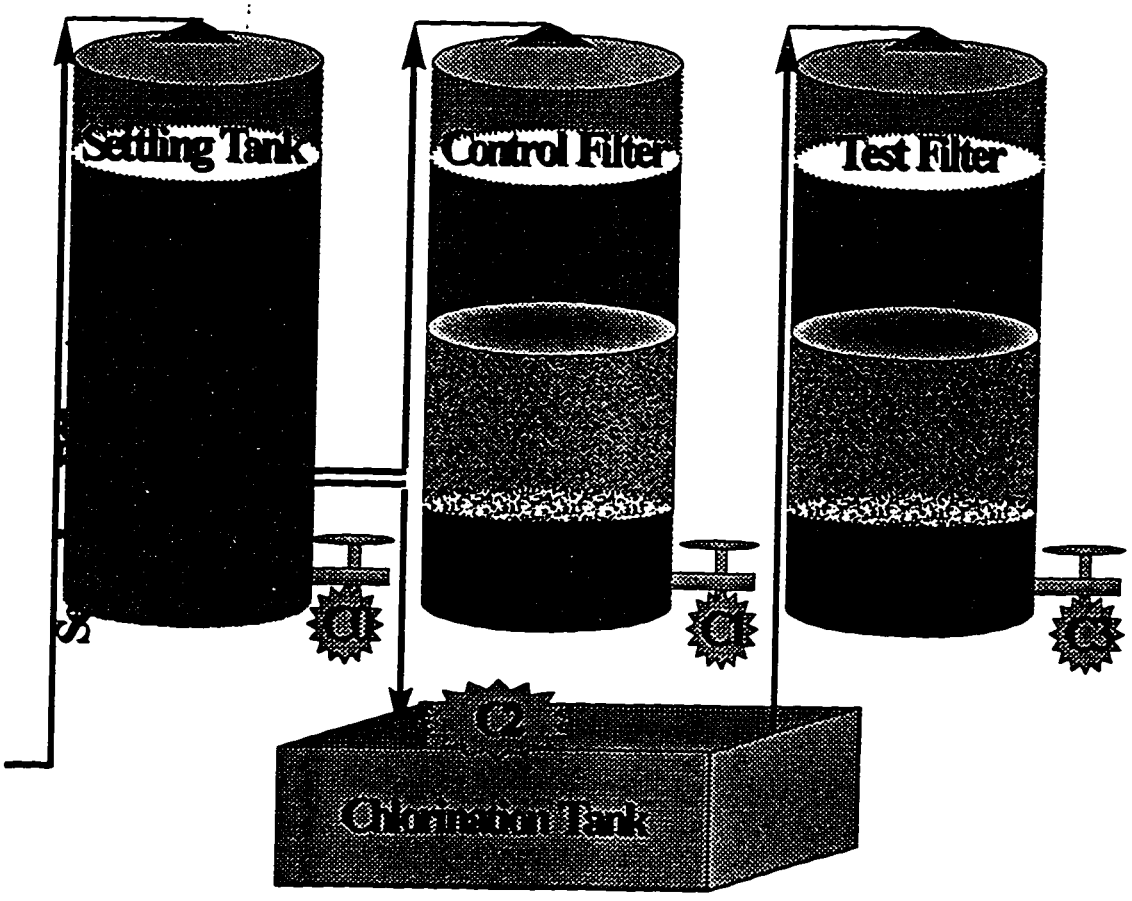


Fig 4.2: Schematic Layout of Pilot Slow Sand Filter Plant

4.2 Al-Khobar Sewage Treatment Plant

The Al-Khobar sewage treatment plant is located in the Eastern Province of Saudi Arabia, approximately 3 km from the city of Al-Khobar. The Plant is designed to handle a daily flow of 133,330 m^3. The basic process used for the treatment of the sewage is the activated sludge process. The principal components of the plant are an inlet structure with screening, grit removal and flow measurement, carousel type aeration tanks, final clarifiers, sludge re-circulation pumping stations, effluent storage lagoons, chlorination facility, sludge thickeners, thickened sludge pumping station, and sludge drying beds.

After the final clarification the treated effluent is disinfected with chlorine and discharged to the Arabian Gulf. Table 4.1 gives some typical characteristics of unchlorinated secondary effluent from the Al-Khobar sewage treatment plant.

4.2.1 Slow Sand Filter Units

Each modular slow sand filter unit consists of a 4 m deep, 2 m internal diameter cylindrical filter box placed 1-1.5 m into the ground. The filter units were constructed of reinforced concrete. A 15 cm circular weir was constructed on the inside of the filter top, to minimize disturbance of the

Parameter	Minimum	Maximum	Average
Temperature °C	10.0	39.0	28.2
Conductivity µmhos/cm	2800	3600	3447
pH	7.3	7.7	7.5
Alkalinity mg/l as $CaCO_3$	95	160	125
DO mg/l	5.0	7.1	6.0
Turbidity NTU	0.20	0.95	0.70
BOD mg/l	2.80	6.10	4.78
COD mg/l	32.0	57.6	41.04
TOC mg/l	11.7	16.8	14.1
Suspended Solids mg/l	8.0	88.4	14.7
TKN mg/l	0	6.16	3.20
Organic-N mg/l	0	6.16	2.70
NO_3 mg/l	0.05	1.30	0.38
NO_2 mg/l	0	1.15	0.56
Total-PO_4 mg/l	0	1.98	1.18
Ortho-PO_4 mg/l	0	1.55	0.63
Chlorides mg/l	424	1119	713
Sulphates mg/l	227	590	285
Total Coliform MPN/100ml	3100	1700000	369000
Fecal Coliform MPN/100ml	0	940000	153000
Standard Plate Count /ml	3200	820000	238000
Coliphage PFU/100ml	100	6200	577
Lead mg/l	0.001	0.132	0.043
Cadmium mg/l	0.004	0.170	0.070
Zinc mg/l	0.193	0.500	0.28
Iron mg/l	0.12	0.30	0.20
Copper mg/l	0.006	0.100	0.056
Nickel mg/l	0.005	0.100	0.034

Table 4.1: Characteristics of Unchlorinated Secondary Effluent from Al-Khobar Sewage Treatment Plant

supernatant water and subsequent erosion of the *schmutzedecke* layer by the feed. Each filter was also equipped with an overflow pipe at the top. Three manometers were installed at a depth of 2.23, 2.64 and 3.56 m to measure variations in the head loss. The headloss in both the test and control filters were measured daily. A sand layer of size 0.5 mm with a uniformity coefficient of 1.6 and a depth of 1 m was placed on a gravel media. Several layers of supporting gravel media with size ranging from 2.5" at the bottom to 0.125" at the interface with the sand ensured that the sand did not clog the underdrain. The outlet for the collection of filter effluents is provided in level with the sand in the filter to prevent negative pressure build-up. Each filter module was equipped with a 1 hp, 60 Hz, single phase pump with corrosion resistant plastic impellers. The hydraulic loading to the filters was constantly adjusted to around 2.3 m/d using the outflow valves at the outlet of each filter. The cross sectional view of a pilot slow sand filter is given in Fig. 4.2. The settling tank is a cylindrical structure designed to hold the secondary effluent for an average retention time of about 4 hr. It is 4 m deep with an internal diameter of 2 m.

The secondary effluents from the treatment plant are first pumped into the settling tank. The settled secondary effluent is then divided into two streams. One stream goes to the control filter and the other is chlorinated in the chlorination tank, before being introduced into the test filter. Both the filters and the tanks have outlets through which the treated samples are collected. The design parameters for the pilot slow sand filters are given in Table 4.2.

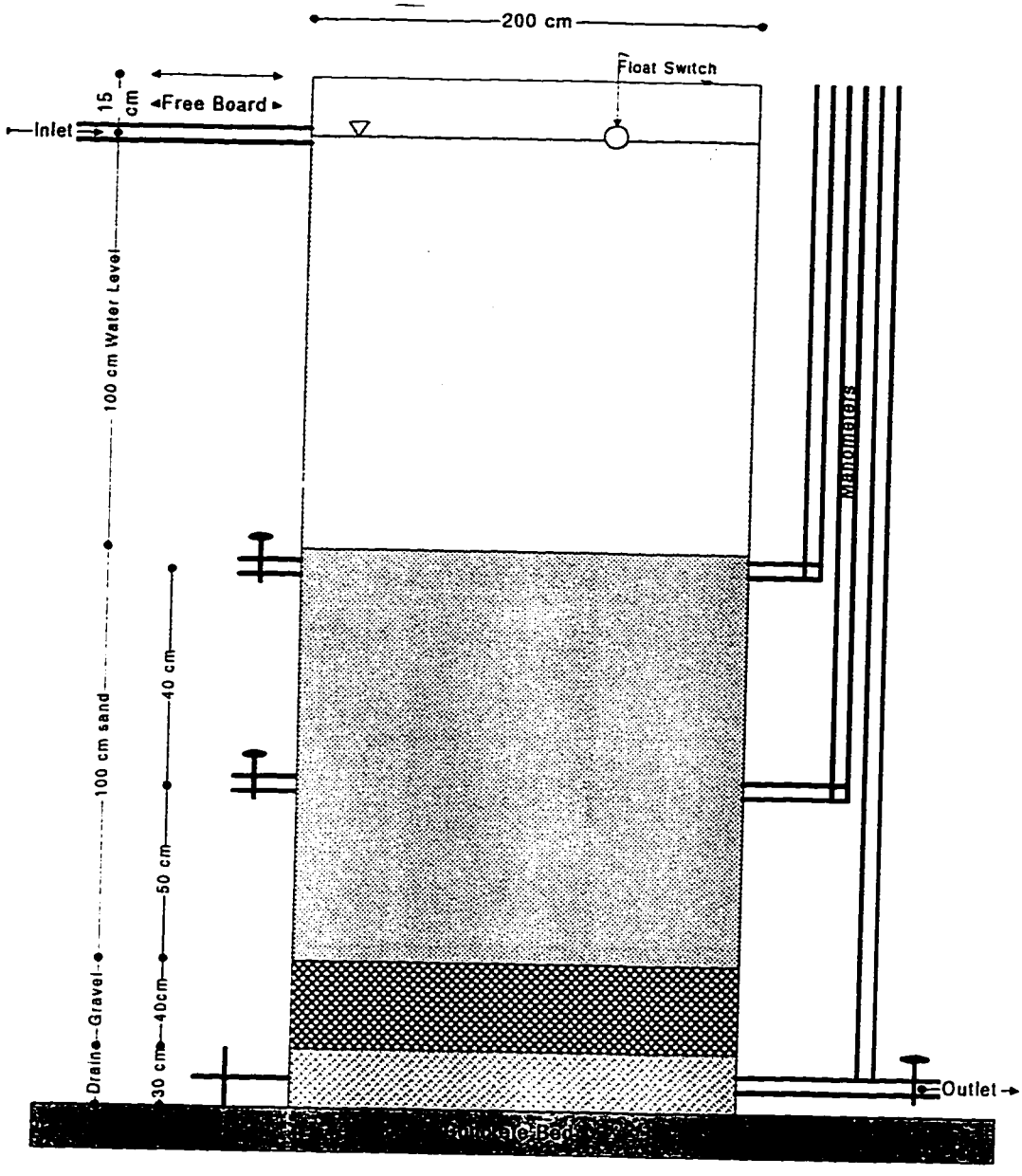


Fig 4. 3 Cross Sectional View of Pilot Slow Sand Filter

Criterion	
Design Period	-
Period of Operation	24 hr
Filtration Rate	0.2 m/hr
Height of Underdrains (Including Gravel)	0.7 m
Height of Supernatent Water	1.0 m
Number of Filter Bed Units	2 Units
Filter Bed Depth	1.0 m
Filter Bed Area	3.14 m^2
Sand Specification	
Effective Size	0.5 mm
Uniformity Coefficient	1.6

Table 4.2:Design Parameters for Pilot Slow Sand Filters

4.3 Materials And Methods

4.3.1 Sample Collection

The samples for the microbial analysis were collected from the settled secondary effluent, chlorination tank outlet, and the outlets from the test and control filters respectively. The sampling points for the various microbial parameters are shown in Fig 4.1 along with the notations used for denoting their numbers. The method of collection of samples was as outlined in the *Standard Methods for the Examination of Water and Wastewater.* Microbial analysis of chlorinated and unchlorinated secondary effluents includes the detection and enumeration of standard plate counts, total coliforms, fecal coliforms, fecal streptococcus, *Clostridium perfringens*, and coliphages. The microbial parameters, the methods of detection and enumeration and the culture media utilized are summarized in Table 4.3.

4.3.2 Analysis of Samples

The detection and enumeration of standard plate counts, total coliforms, fecal coliforms, fecal streptococci and coliphages were as recommended by *Standard Methods for the Examination of Water and*

Microbial Parameter	**Method of Detection and Enumeration**	**Culture Media**
Standard Plate Counts	Pour plate technique	Standard Method Agar
Total Coliforms	MPN method	Lactose broth and BGB broth
Fecal Coliforms	MPN method	EC broth
Fecal Streptococcus	MPN method	Azide Dextrose Broth
Clostridium perfringens	Membrane filter technique	Enriched Clostridial Agar
Coliphages	Plaque forming units in a lawn of E. coli host cells	Tryptic Soy Agar, Tryptic Soy Broth, and Modified Tryptic Soy Agar.

Table 4.3: Detection and Enumeration Techniques and Culture Media to be Used.

Wastewater. Clostridium perfringens was enumerated by the process outlined by the *International Standards Organization for the Examination of Drinking Water.* The analysis for all the parameters was carried out weekly to monitor the removal of the microbial indicator organisms and filter efficiency.

The removal efficiencies of microbial parameters was found out for the three different levels of treatment, namely, slow sand filtration alone, chlorination alone and the combined removals due to chlorination and subsequent slow sand filtration. The percent removals for the different schemes were calculated as explained in the Results and Discussions.

4.3.3 Headloss Measurements

Headloss readings were taken daily at three manometers installed at depths of 2.23, 2.64 and 3.56 m from the ground level to measure variations in the head loss. The headloss readings were taken in both the control and test filters.

4.4 Analysis of Data Using Interaction Model

Studies show that slow sand filters are biological filters and there is concern that prechlorination may lead to reduced removal efficiency in the

filters. A model therefore is needed to examine the effect of prechlorination on slow sand filter efficiency in the removal of bacteria and viruses. The effect of prechlorination dose on the filtration efficiency of slow sand filters can be studied using the Berenbaums Interaction Model [Kaume and Haas, 1991; Straub *et al*, 1994].

As it became increasingly important to combine agents (drugs and chemicals) in order to enhance their effectiveness against diseases and the microorganisms responsible for diseases, it was also important to be able to express mathematically the effect produced by the agents in the combination so that the observation of the activities could be quantified, and in some cases predicted. A general solution to determine the kind of interaction which can be expected when the agents are combined to produce a given effect has been proposed by Berenbaum in 1981 [Kaume and Haas, 1991; Straub *et al*, 1994]. The principle is that, if the agents in a given combination do not interact in producing the effect observed, then regardless of the dose-effect relations, the following equation is satisfied.

$$\sum_{i=1}^{n} \frac{x_i}{y_i} = 1$$

Where,

x_i = concentration of the individual agent in the combination

y_i = concentration of the agents that individually would produce the same magnitude of effect as that of the combination

i = individual agent

n = total number of agents

The equation is interpreted as follows:

The sum is less than 1 in the case of synergistic interaction. $\left(\sum_{i=1}^{n}\frac{x_i}{y_i}<1\right)$

The sum is greater than 1 in case of antagonistic interaction. $\left(\sum_{i=1}^{n}\frac{x_i}{y_i}>1\right)$

The sum is equal to 1 in the case of additivity (zero interaction). $\left(\sum_{i=1}^{n}\frac{x_i}{y_i}=1\right)$

A combination of agents that is more effective than is expected from the single component effectiveness of its constituents is said to show synergy. Conversely if a larger dose is required to produce a given effect when the agents are combined than when they are used separately, then the interaction is said to be antagonistic. For agents which in the combination are no more and no less effective than when they are used separately, the interaction is said to be additive.

The method proposed by Berenbaum (1985) allows one to determine if an additive, synergistic or antagonistic interaction has occurred between agents in a given combination. It establishes a relationship between dose and effect of the individual agent in a combination. This study can be applied to the analysis of a mixed system data. In the case of distributed data, any

relevant distribution can be used to evaluate the dose required to achieve a desired effect.

A similar approach was adopted by Kaume and Haas (1991), to determine the effect of the combined action of free chlorine and monochloramine on the inactivation of *E. coli*.

4.4.1 Modified Interaction Model for Use with Non-Quantifiable Agents

The method proposed by Berenbaum for the interaction analysis between various combinations of agents has an obvious drawback when used to analyze the behavior of non-quantifiable agents. This is evident in the case of slow sand filtration which cannot be expressed in terms of dose. Thus the Berenbaums equation must be modified to include non-quantifiable agents. This can be done on the assumption that dose is directly proportional to the effect, an assumption that is the basis for the Berenbaum equation, and replacing the dose by the probable effect $P(R \leq x)$ in the equation. Thus the modified Berenbaum equation for non-quantifiable agents takes the form of

$$\sum_{i=1}^{n} \frac{P(R \leq x_i)}{P(R \leq y_i)} = 1$$

where,

$P(R \leq x_i)$ = probability that the removals x_i due to an agent would be less than or equal to any given removal R

$P(R \leq y_i)$ = probability that the removals y_i in the system would be less than or equal to any given removal R

i = individual agent

n = total number of agents

Also the interaction factor $\left[\sum_{i=1}^{n} \frac{P(R \leq x_i)}{P(R \leq y_i)}\right]$ gives an estimate of the extent of interaction between the different treatment processes. A greater degree of synergistic interaction is expected as the interaction factor approaches 0. A value between 0 and 1 will imply synergistic interaction between the two treatment processes. An adverse interaction is interpreted when the interaction factor exceeds 1.

Straub *et.al* (1994), have outlined the procedure for the testing for synergism. They demonstrated the ability of the Berenbaums equation to successfully explain the synergistic inactivation of *E. coli* and MS-2 coliphage by chloramine and cupric chloride.

CHAPTER #5

5. RESULTS AND DISCUSSIONS

Two slow sand filters were operated in parallel for a period of 6 months to monitor and investigate the removal efficiencies of various indicator organisms, namely, standard plate counts, total coliform, fecal coliform, fecal streptococcus, *Clostridium perfringens* and coliphage. One slow sand filter was utilized to treat settled secondary effluent from the Al-Khobar Sewage Treatment Plant. This acted as control filter to enable comparisons to be made. The second filter, called as test filter, was utilized to treat the chlorinated settled secondary effluent. The chlorination chamber was incorporated into the effluent tank from which the chlorinated settled secondary effluent was supplied to the test filter. In order to maintain identical conditions the sand size, depth of sand media, and flow rate were kept the same in order to facilitate comparisons. The flow rate was maintained at 10 l/min, throughout the period of the study, in both the filters. The sand size was 0.5 mm with a depth of sand media at 1.0 m.

The study was conducted in two phases. In Phase I the chlorine dose was kept at 5 mg/l. Phase II which commenced 2 weeks after Phase I utilized a chlorine dose of 15 mg/l.

The objective of the study was to evaluate the microbial removals in the slow sand filters, treating pre-chlorinated secondary effluents. This chapter discusses the results obtained during the study, and a comparison is made between the removals in the control filter and the test filter (under both the phases).

5.1 Removal of Indicator Organisms

The study was conducted in two phases, in which the only criteria that was changed was the chlorine dose. Analysis was carried out for the detection and enumeration of six indicator microorganisms namely, standard plate count, total coliforms, fecal coliform, fecal streptococcus, *Clostridium perfringens*, and coliphages. The samples for the microbial evaluation were taken form the chlorinated and chlorinated settled secondary effluent and from the outlets of the test and control filters. The data was analyzed to find the removal of the different microorganisms by chlorination, slow sand filtration and prechlorinated slow sand filtration.

5.1.1 Removal in Control Slow Sand Filter

The control filter was utilized for the comparative evaluation of the filter efficiency due to both chlorination alone and the combined treatment in the test filter. Table 5.1 gives the actual populations of standard plate count in the settled secondary effluent, under C0 (COL#2). After control slow sand filtration the effluent from the control filter was again analyzed for the standard plate count these values are given under C1 (COL#3). The percentage removals in the control filter were calculated as,

$$R1 = \frac{C0 - C1}{C0} * 100$$

Where,

R1 = Removal of indicator organisms in control filter

C0 = Actual population of the indicator organisms in the settled secondary effluent

C1 = Actual population of the indicator organisms in the effluent from control filters

Therefore for day 1 for standard plate count during Phase I

C0 = 17000 and C1 = 1800

Therefore by substituting in the above equation

Table 5.1: Variation and Removal of Standard Plate Count During Phase I

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (/ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	17000	1800	480	75	89.412	97.176	99.559	84.375
7	3850	400	367	70	89.610	90.468	98.182	80.926
9	4210	720	600	110	82.898	85.748	97.387	81.667
10	4900	578	650	90	88.204	86.735	98.163	86.154
12	9800	1050	3500	190	89.286	64.286	98.061	94.571
19	9000	680	1500	300	92.444	83.333	96.667	80.000
26	25000	2500	1400	25	90.000	94.400	99.900	98.214
33	38500	3800	9000	60	90.130	76.623	99.844	99.333
42	4200	820	480	25	80.476	88.571	99.405	94.792
47	7460	1200	800	150	83.914	89.276	97.989	81.250
52	42000	5200	500	26	87.619	98.810	99.938	94.800
53	38500	3800	2900	500	90.130	92.468	98.701	82.759
MIN	3850	400	367	25	80.476	64.286	96.667	80.000
MAX	42000	5200	9000	500	92.444	98.810	99.938	99.333
AVG	17035	1879	1848	135	87.844	87.324	98.650	88.237

Table 5.2: Variation and Removal of Standard Plate Count During Phase II

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (/ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	18400	1600	20	3	91.304	99.891	99.984	85.000
7	34500	2500	10	3	92.754	99.971	99.991	70.000
14	4200	810	25	3	80.714	99.405	99.929	88.000
16	9800	1200	40	5	87.755	99.592	99.949	87.500
19	4900	580	35	4	88.163	99.286	99.918	88.571
21	8400	620	30	4	92.619	99.643	99.952	86.667
23	35000	2400	32	3	93.143	99.909	99.991	90.625
26	62500	3800	26	5	93.920	99.958	99.992	80.769
28	7200	790	21	6	89.028	99.708	99.917	71.429
33	7350	980	28	3	86.667	99.619	99.959	89.286
35	56000	5200	40	5	90.714	99.929	99.991	87.500
37	58300	3980	42	6	93.173	99.928	99.990	85.714
MIN	4200	580	10	3	80.714	99.286	99.917	70.000
MAX	62500	5200	42	6	93.920	99.971	99.992	90.625
AVG	25546	2038	29	4	89.996	99.737	99.964	84.255

$$R1 = \frac{17000 - 1800}{17000} * 100 = 89.41\%$$

5.1.2 Removal Due to Chlorination

In this study two chlorination doses were selected for the evaluation of prechlorination which comprised of two phases. Phase I utilized a prechlorinating dose of 5 mg/l and Phase II had a prechlorinating dose of 15 mg/l. The effect of these chlorination doses alone on the microbial removals can be studied from the chlorination efficiency expressed as the percent removal of the microorganisms. The effluent from the chlorination tank was also enumerated for the standard plate counts and these values are given under C2 (COL#3) in Table 5.1. The percent removal of the microbial indicators due to chlorination in the chlorine tank is found as follows,

$$R2 = \frac{C0 - C2}{C0} * 100$$

Where,

R2 = Removal of microbial parameter due to chlorination

C2 = Actual population of the indicator organisms in the effluent from chlorination tank

Therefore for day 1 for standard plate count during Phase I

C0 = 17000 and C2 = 480

Therefore by substituting in the above equation

$$R2 = \frac{17000 - 480}{17000} * 100 = 97.17\%$$

5.1.3 Overall Removal in Test Filter

In the test filter the combined removals due to chlorination and subsequent slow sand filtration was studied. This will provide a comparison for the expected enhanced removals due to prechlorination in slow sand filters. C3 (COL# 5) in Table 5.1 gives the actual population of the standard plate counts in the effluent from the test filter. The overall removals in the test filter were calculated as,

$$R3 = \frac{C0 - C3}{C0} * 100$$

Where,

R3 = Combined removal of microbial parameter due to chlorination and subsequent slow sand filtration

C3 = Actual population of the indicator organisms in the effluent from test filter

Therefore for day 1 for standard plate count during Phase I

C0 = 17000 and C3 = 75

Therefore by substituting in the above equation

$$R3 = \frac{17000 - 75}{17000} * 100 = 99.55\%$$

The percent removals in the control filter are termed as R1 (COL#6). R2 (COL#7) represents the removal due to chlorination alone and R3 (COL#8) represents the removals due to the test filtration that incorporates the combined effect of the chlorination and subsequent slow sand filtration.

5.1.4 Removal in Test Filter

In order to compare the effect of chlorination on the filter itself the partial removals due to the effect of the test filter alone R4 (COL#9) were compared with the removals in the control filter. These values are not exactly comparable because of the presence of a residual chlorine in the test filter and its probable effect on microbial removals throughout the test filter. Nevertheless it was found that the partial removals in the test filter were either similar or better than those in the control filter. The partial removals in the test filter are termed as R4. This will provide a comparison for the expected enhanced removals due to prechlorination in slow sand filters. C3 (COL# 5) in Table 5.1 gives the actual population of the standard plate counts in the

effluent from the test filter. The removals in the chlorinated test filter were calculated as,

$$R4 = \frac{C2 - C3}{C2} * 100$$

Where,

R4 = removal of microbial parameter due to test slow sand filtration alone

C3 = Actual population of the indicator organisms in the effluent from test filter

Therefore for day 1 for standard plate count during Phase I

C2 = 480 and C3 = 75

Therefore by substituting in the above equation

$$R4 = \frac{480 - 75}{480} * 100 = 84.37\%$$

The minimum, maximum and averages of all the different columns is given in the shaded part of the table. The averages for the removals were calculated from their respective columns and not from the average influent and effluent values of the microbial populations.

The corresponding populations and removals of the standard plate count during Phase II which utilized a chlorine dose of 15 mg/l are given in Table 5.2. The data for total coliform during Phase I and II are given in Table

5.3 and 5.4 respectively. Table 5.5 and Table 5.6 give the corresponding values for the fecal coliform during Phase I and II respectively. Similarly the populations and removals of fecal streptococcus for Phase I and II are given in Tables 5.7 and 5.8 respectively. The respective populations and removals for the *Clostridium perfringens* during Phase I and II are given in Table 5.9 and Table 5.10. The coliphage removals and populations in phase I and II are given in Table 5.11 and 5.12 respectively. These results are discussed separately in the next section.

5.2 Phase I : Chlorine dose of 5 mg/l

5.2.1 Standard Plate Count

During the first phase of the study, standard plate counts in the settled secondary effluent varied from $4.2x10^4$/ml to $3.85x10^3$/ml, with an average around $1.7x10^4$. After filtration in the control slow sand filter these were reduced to $5.2x10^3$ to $4.0x10^2$ with an average of $1.85x10^3$. This represents an average removal of 87.8% in the control filter. After chlorination with a chlorine dose of 5 mg/l, the standard plate count ranged from $9.0x10^3$ to $3.67x10^2$ with an average around $1.85x10^3$, representing an average reduction of 87.3% by chlorination alone. After filtration in the test filter, these were further reduced

Table 5.3: Variation and Removal of Total Coliform During Phase I

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (MPN/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	170000	26000	54000	7000	84.706	68.235	95.882	87.037
7	530000	45000	55000	2400	91.509	89.623	99.547	95.636
9	280000	50000	80000	4900	82.143	71.429	98.250	93.875
10	260000	35000	65000	5800	86.538	75.000	97.769	91.077
12	90000	18000	20000	1800	80.000	77.778	98.000	91.000
19	600000	71000	90000	2300	88.167	85.000	99.617	97.444
26	330000	52000	79000	4500	84.242	76.061	98.636	94.304
33	540000	92000	160000	6800	82.963	70.370	98.741	95.750
42	280000	50000	80000	9800	82.143	71.429	96.500	87.750
47	82000	30000	20000	2000	63.415	75.610	97.561	90.000
52	280000	50000	80000	5200	82.143	71.429	98.143	93.500
53	720000	53000	93000	2400	92.639	87.083	99.667	97.419
MIN	82000	18000	20000	1800	63.415	68.235	95.882	87.037
MAX	720000	92000	160000	9800	92.639	89.623	99.667	97.444
AVG	346833	47667	73000	4575	83.384	76.587	98.193	92.899

Table 5.4: Variation and Removal of Total Coliform During Phase II

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (MPN/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	70000	6200	60	2	91.143	99.914	99.997	96.667
7	110000	22000	90	4	80.000	99.918	99.996	95.556
14	90000	16000	110	6	82.222	99.878	99.993	94.545
16	130000	20000	40	7	84.615	99.969	99.995	82.500
19	140000	32000	110	4	77.143	99.921	99.997	96.364
21	170000	33000	40	12	80.588	99.976	99.993	70.000
23	60000	11000	60	13	81.667	99.900	99.978	78.333
26	140000	27000	50	2	80.714	99.964	99.999	96.000
28	90000	20000	120	11	77.778	99.867	99.988	90.833
33	170000	33000	110	8	80.588	99.935	99.995	92.727
35	140000	26000	60	4	81.429	99.957	99.997	93.333
37	90000	16000	40	4	82.222	99.956	99.996	90.000
MIN	60000	6200	40	2	77.143	99.867	99.978	70.000
MAX	170000	33000	120	13	91.143	99.976	99.999	96.667
AVG	116667	21850	74	6	81.676	99.930	99.994	89.738

Table 5.5: Variation and Removal of Fecal Coliform During Phase I

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (MPN/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	120000	13000	35000	7000	89.167	70.833	94.167	80.000
7	350000	32000	90000	4300	90.857	74.286	98.771	95.222
9	150000	35000	17000	3000	76.667	88.667	98.000	82.353
10	65000	8200	5000	1300	87.385	92.308	98.000	74.000
12	80000	20000	11000	2000	75.000	86.250	97.500	81.818
19	400000	26000	23000	2500	93.500	94.250	99.375	89.130
26	26000	1500	9000	380	94.231	65.385	98.538	95.778
33	500000	70000	58000	5000	86.000	88.400	99.000	91.379
42	180000	35000	17000	3300	80.556	90.556	98.167	80.588
47	64000	12000	11000	1500	81.250	82.813	97.656	86.364
52	220000	35000	16000	1050	84.091	92.727	99.523	93.438
53	65000	4200	5000	640	93.538	92.308	99.015	87.200
MIN	26000	1500	5000	380	75000	65385	94167	74000
MAX	500000	70000	90000	7000	94231	94250	99523	95778
AVG	185000	24325	24750	2664	86020	84898	98143	86439

Table 5.6: Variation and Removal of Fecal Coliform During Phase II

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (MPN/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	50000	9000	40	1	82.000	99.920	99.998	97.500
7	80000	15000	50	2	81.250	99.938	99.998	96.000
14	70000	12000	70	4	82.857	99.900	99.994	94.286
16	110000	17000	28	4	84.545	99.975	99.996	85.714
19	110000	21000	35	2	80.909	99.968	99.998	94.286
21	140000	27000	22	7	80.714	99.984	99.995	68.182
23	35000	6000	30	6	82.857	99.914	99.983	80.000
26	130000	22000	16	2	83.077	99.988	99.998	87.500
28	70000	20000	50	7	71.429	99.929	99.990	86.000
33	130000	33000	28	4	74.615	99.978	99.997	85.714
35	90000	2600	40	2	97.111	99.956	99.998	95.000
37	60000	16000	22	2	73.333	99.963	99.997	90.909
MIN	35000	2600	16	1	71429	99900	99983	68182
MAX	140000	33000	70	7	97111	99988	99998	97500
AVG	89583	16767	36	4	81225	99951	99995	88424

Table 5.7: Variation and Removal of Fecal Streptococcus During Phase I

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (MPN/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	13000	1100	7000	900	91.538	46.154	93.077	87.143
7	18000	830	11000	450	95.389	38.889	97.500	95.909
9	18000	5000	7100	240	72.222	60.556	98.667	96.620
10	13000	3500	1100	110	73.077	91.538	99.154	90.000
12	5000	900	2300	200	82.000	54.000	96.000	91.304
19	30000	2500	1600	230	91.667	94.667	99.233	85.625
26	1300	200	320	52	84.615	75.385	96.000	83.750
33	32000	6800	4900	1400	78.750	84.688	95.625	71.429
42	20000	5000	1800	250	75.000	91.000	98.750	86.111
47	4800	900	2300	20	81.250	52.083	99.583	99.130
52	20000	5500	1700	240	72.500	91.500	98.800	85.882
53	12000	1200	1100	170	90.000	90.833	98.583	84.545
MIN	1300	200	320	20	72.222	38.889	93.077	71.429
MAX	32000	6800	11000	1400	95.389	94.667	99.583	99.130
AVG	15592	2786	3518	355	82.334	72.608	97.581	88.121

Table 5.8: Variation and Removal of Fecal Streptococcus During Phase II

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (MPN/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	4000	700	8	1	82.500	99.800	99.975	87.500
7	7000	500	11	1	92.857	99.843	99.986	90.909
14	5000	700	4	2	86.000	99.920	99.960	50.000
16	3000	400	9	2	86.667	99.700	99.933	77.778
19	32000	1400	11	1	95.625	99.966	99.997	90.909
21	7000	1100	9	1	84.286	99.871	99.986	88.889
23	2600	400	8	2	84.615	99.692	99.923	75.000
26	4000	500	7	4	87.500	99.825	99.900	42.857
28	5000	700	11	4	86.000	99.780	99.920	63.636
33	7000	1100	8	2	84.286	99.886	99.971	75.000
35	9000	1000	7	1	88.889	99.922	99.989	85.714
37	5000	700	11	4	86.000	99.780	99.920	63.636
MIN	2600	400	4	1	82.500	99.692	99.900	42.857
MAX	32000	1400	11	4	95.625	99.966	99.997	90.909
AVG	7550	767	9	2	87.102	99.832	99.955	74.319

Table 5.9: Variation and Removal of *Clostridium perfringens* During Phase I

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	62	8	54	6	87.097	12.903	90.323	88.889
7	102	13	63	14	87.255	38.235	86.275	77.778
9	24	4	18	2	83.333	25.000	91.667	88.889
10	23	2	8	1	91.304	65.217	95.652	87.500
12	23	7	15	2	69.565	34.783	91.304	86.667
19	54	9	43	4	83.333	20.370	92.593	90.698
26	181	23	113	11	87.293	37.569	93.923	90.265
33	133	70	75	30	47.368	43.609	77.444	60.000
42	124	27	53	11	78.226	57.258	91.129	79.245
47	86	19	39	11	77.907	54.651	87.209	71.795
52	516	82	99	19	84.109	80.814	96.318	80.808
53	160	64	58	32	60.000	63.750	80.000	44.828
MIN	23	2	8	1	47.368	12.903	77.444	44.828
MAX	516	82	113	32	91.304	80.814	96.318	90.698
AVG	124	27	53	12	78.066	44.513	89.486	78.947

Table 5.10: Variation and Removal of *Clostridium perfringens* During Phase II

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	130	22	60	4	83.077	53.846	96.923	93.333
7	320	60	220	6	81.250	31.250	98.125	97.273
14	280	58	160	8	79.286	42.857	97.143	95.000
16	400	82	28	8	79.500	93.000	98.000	71.429
19	260	54	12	2	79.231	95.385	99.231	83.333
21	310	58	12	6	81.290	96.129	98.065	50.000
23	320	60	16	4	81.250	95.000	98.750	75.000
26	400	90	18	3	77.500	95.500	99.250	83.333
28	120	30	50	1	75.000	58.333	99.167	98.000
33	180	40	80	5	77.778	55.556	97.222	93.750
35	400	70	96	7	82.500	76.000	98.250	92.708
37	300	50	110	2	83.333	63.333	99.333	98.182
MIN	120	22	12	1	75.000	31.250	96.923	50.000
MAX	400	90	220	8	83.333	96.129	99.333	98.182
AVG	285	56	72	5	80.083	71.349	98.288	85.945

Table 5.11: Variation and Removal of Coliphage During Phase I

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (PFU/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	450	63	340	41	86.000	24.444	90.889	87.941
7	450	63	340	41	86.000	24.444	90.889	87.941
9	384	46	112	14	88.021	70.833	96.354	87.500
10	620	73	410	19	88.226	33.871	96.935	95.366
12	572	101	396	33	82.343	30.769	94.231	91.667
19	434	98	227	31	77.419	47.696	92.857	86.344
26	550	30	320	1	94.545	41.818	99.818	99.688
33	890	60	250	50	93.258	71.910	94.382	80.000
42	770	182	336	88	76.364	56.364	88.571	73.810
47	1360	540	700	420	60.294	48.529	69.118	40.000
52	2420	800	470	300	66.942	80.579	87.603	36.170
53	340	130	140	20	61.765	58.824	94.118	85.714
MIN	340	30	112	1	60.294	24.444	69.118	36.170
MAX	2420	800	700	420	94.545	80.579	99.818	99.688
AVG	770	182	337	88	80.098	49.173	91.314	79.345

Table 5.12: Variation and Removal of Coliphage During Phase II

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	Actual Population (PFU/100ml)				Percent Removals			
Days	C0	C1	C2	C3	R1	R2	R3	R4
1	400	90	90	3	77.500	77.500	99.250	96.667
7	2000	370	600	5	81.500	70.000	99.750	99.167
14	1800	330	500	4	81.667	72.222	99.778	99.200
16	1200	220	500	2	81.667	58.333	99.833	99.600
19	800	170	260	6	78.750	67.500	99.250	97.692
21	1200	220	260	6	81.667	78.333	99.500	97.692
23	300	70	80	1	76.667	73.333	99.667	98.750
26	400	90	80	5	77.500	80.000	98.750	93.750
28	1300	270	400	7	79.231	69.231	99.462	98.250
33	500	11	150	2	97.800	70.000	99.600	98.667
35	1100	220	400	3	80.000	63.636	99.727	99.250
37	900	19	300	1	97.889	66.667	99.889	99.667
MIN	300	11	80	1	76.667	58.333	98.750	93.750
MAX	2000	370	600	7	97.889	80.000	99.889	99.667
AVG	992	173	302	4	82.653	70.563	99.538	98.196

to range between $5.00x10^2$ to $2.5x10^1$ and averaged at $1.35x10^2$ representing an overall removal of 98.6%. The variations in the standard plate count during Phase I in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig. 5.1, which is obtained as a plot of COL#1 of Table 5.1 on the X-axis vs. COL#2, 3, 4, and 5 on the Y-axis. The corresponding standard plate count removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.2, which is obtained as a plot of COL#1 of Table 5.1 on the X-axis vs. COL#6, 7, 8, and 9 on the Y-axis. Similar plots were obtained for the different indicator microorganisms from their corresponding plots. It was observed that the overall removals in the test filter were considerably better than those due to either chlorination or filtration alone. Large variations in the removal rates were observed in chlorination and filtration in the control filter. The removals in the test filter were however consistent and had a very narrow range of variation.

5.2.2 Total Coliform

The total coliforms in the settled secondary effluent ranged from $7.2x10^5$ to $8.2x10^4$ and averaged at $3.47x10^5$. The total coliforms in the effluent from the control filter ranged from $9.2x10^4$ to $1.8x10^4$ averaging around $4.77x10^4$. The average removals in the control filter being83.4%.

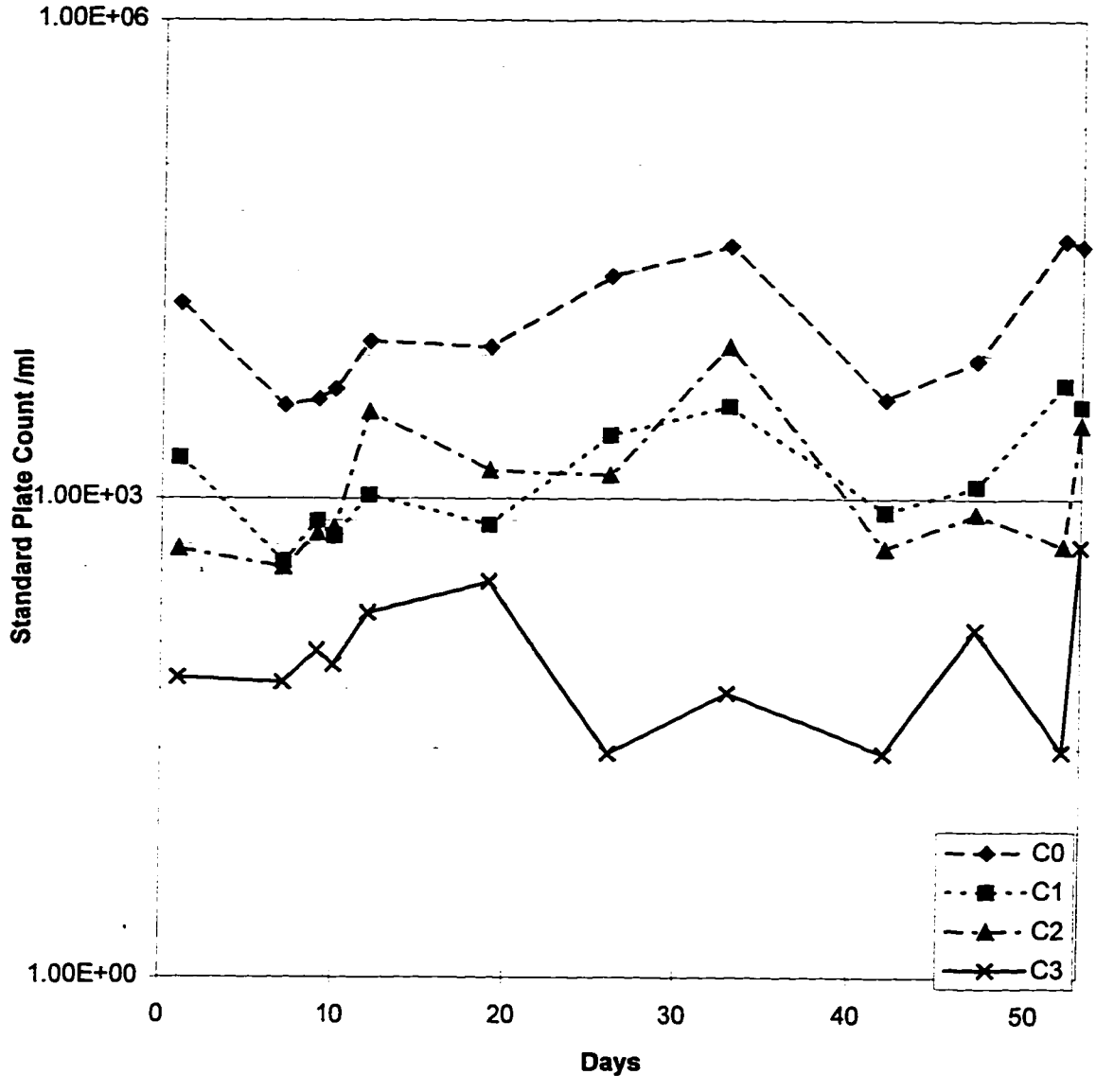


Fig 5.1 : Variation of Standard Plate Count During Phase I

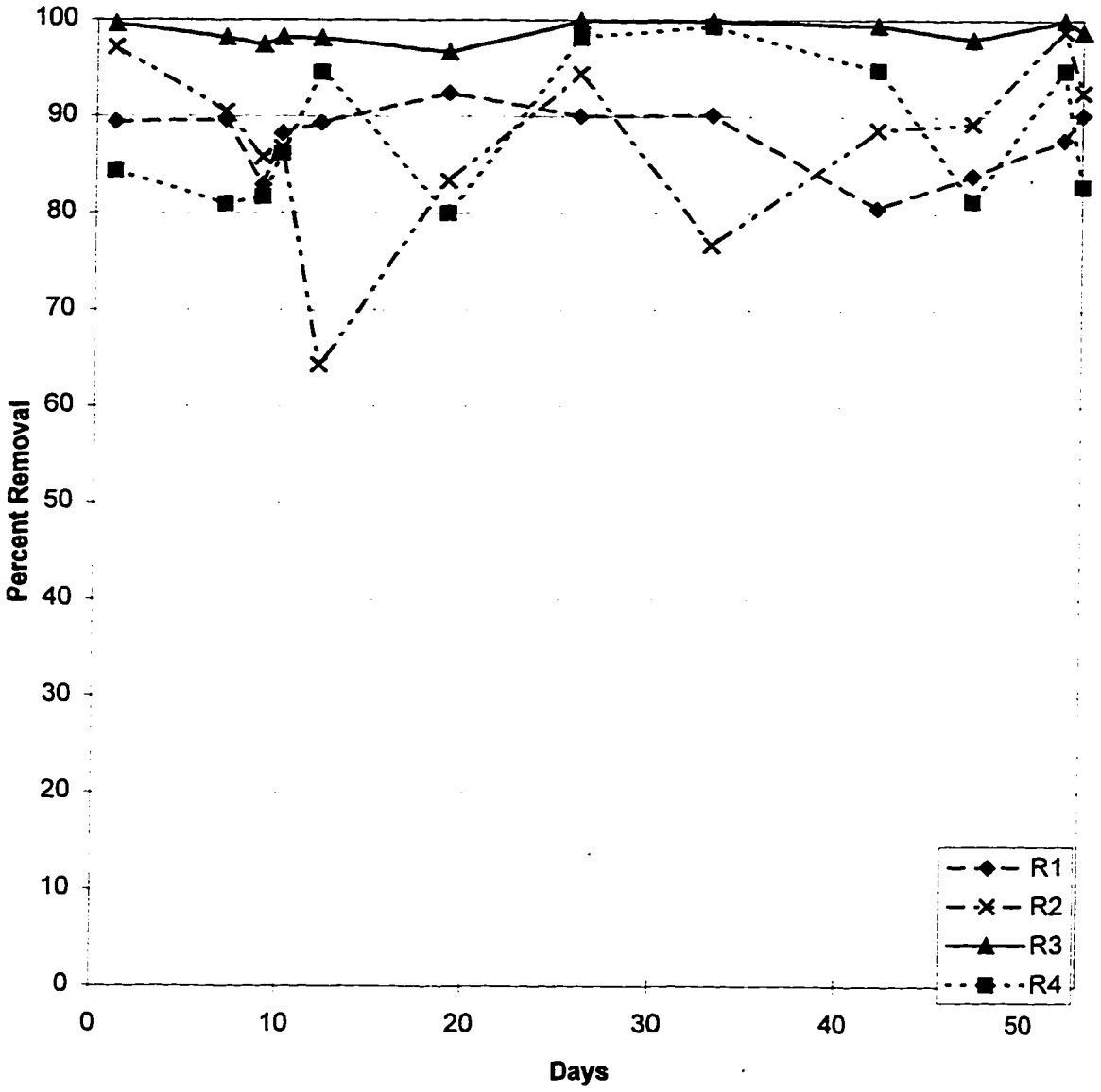


Fig 5.2 : Removal of Standard Plate Count During Phase I

Chlorination of the settled secondary effluent reduced the total coliforms to the range of $1.6x10^5$ to $2.0x10^4$ with an average of $7.3x10^4$. This gives an average removal of 76.6% by chlorination alone. After filtration in the test slow sand filter, the total coliforms ranged between $9.8x10^3$ to $1.8x10^3$, averaging at $4.58x10^3$. Thus the overall removal of total coliforms was 98.2%. The variations in the total coliform during Phase I in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig. 5.3. The corresponding total coliform removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.4. It should be noted that the overall removals in the slow sand filters were on the higher side. This can be adequately explained by the microbial regrowth in the underdrains and the outlets. coliform occurrences have been reported in literature even in the presence of residual chlorine of 4-5 mg/l after a contact time of 1-2 hours [LeChevallier *et al*, 1992]. The recommended procedure is to post disinfect using a nominal chlorine dose.

5.2.3 Fecal Coliform :

In the first phase of the study, the fecal coliform in the settled secondary effluent ranged from $5.0x10^5$ to $2.6x10^4$ and averaged at $1.85x10^5$. After filtration in the control filter, these were reduced to in the range of $7.0x10^4$to $1.5x10^3$ with an average at $2.43x10^4$, representing an average

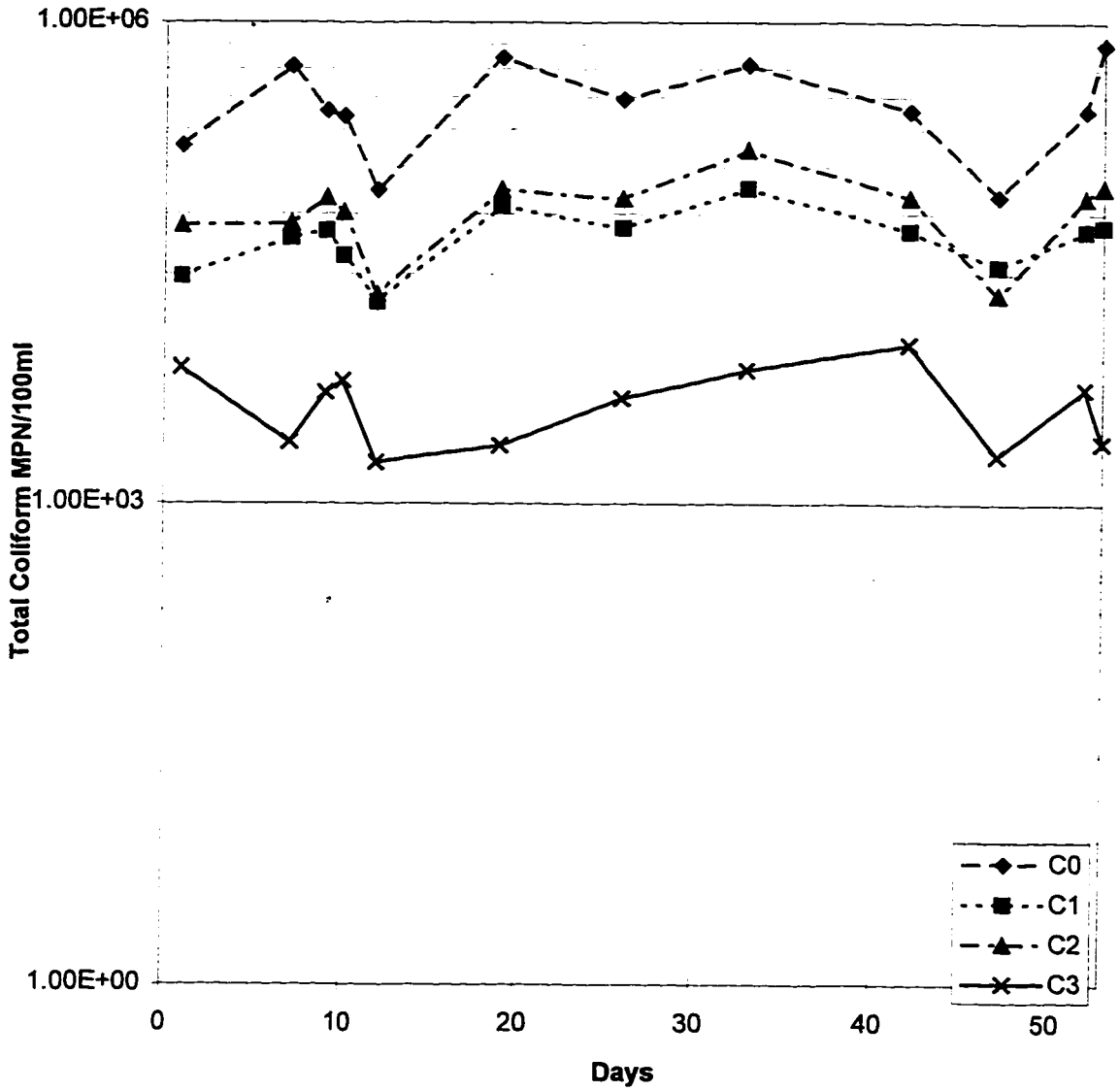


Fig 5.3 : Variation of Total Coliform During Phase I

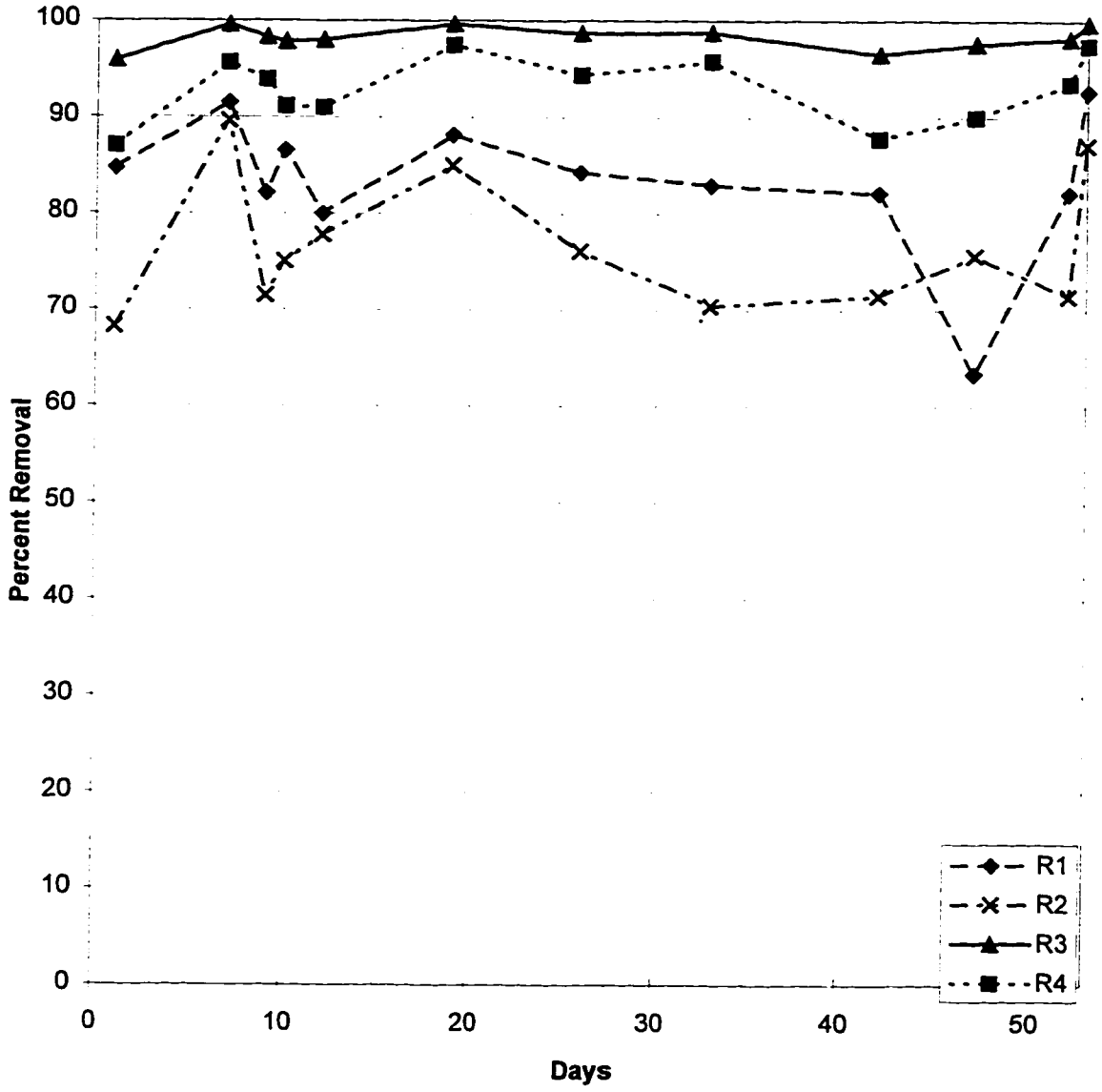


Fig 5.4 : Removal of Total Coliform During Phase I

removal of 81.67%. Chlorination of the settled secondary effluent yielded fecal coliform in the range of $9.0x10^4$ to $5.0x10^3$, and averaged at $2.48x10^4$ giving an average removal of 84.9%. Filtration in the test filter further reduced the fecal coliform to range between $7.0x10^3$ to $3.8x10^2$ and averaged at $2.66x10^3$ giving an overall average removal of 98.1%. The variations in the fecal coliform during Phase I in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig. 5.5. The corresponding fecal coliform removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.6.

5.2.4 Fecal Streptococcus :

The fecal streptococcus in the settled secondary effluent ranged between $3.2x10^4$ to $1.3x10^3$ and averaged at $1.56x10^4$. After filtration in the control filter these were reduced to the range of $6.8x10^3$ to $2.0x10^2$ and averaged at $2.79x10^3$. This implies a removal of 82.3% in the control filter. Chlorination of the settled secondary effluent yielded fecal streptococcus in the range of $1.1x10^4$ to $3.2x10^2$ and averaging at $3.52x10^3$, resulting in a removal of 72.6% due to chlorination alone. After filtration in the test filter the fecal streptococcus ranged between $1.4x10^3$ to $2.0x10^1$ and averaged at $3.55x10^2$, giving an average overall removal of 97.58%. The variations in the fecal streptococcus during Phase I in the settled secondary effluent, effluent

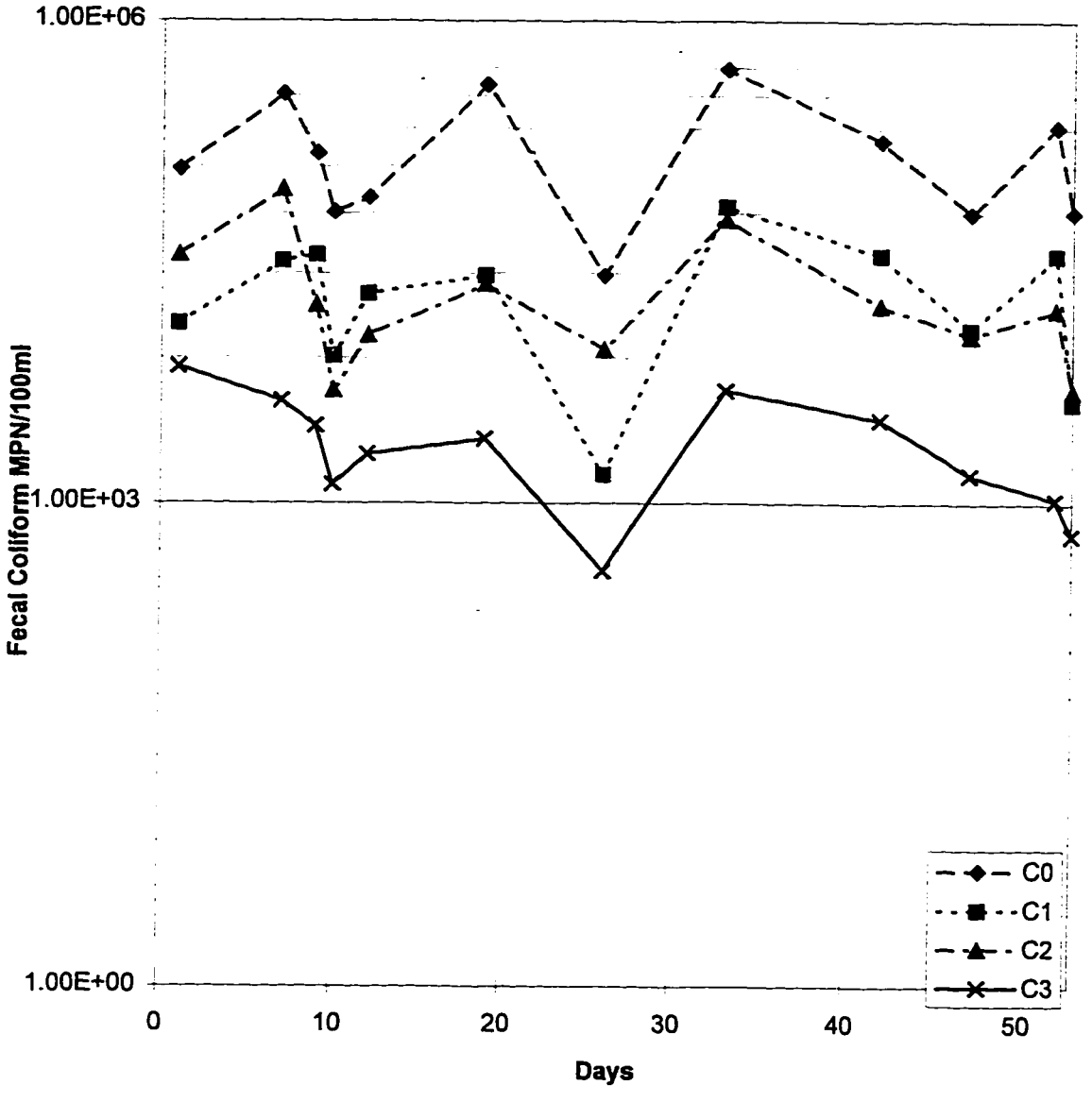


Fig 5.5 : Variation of Fecal Coliform During Phase I

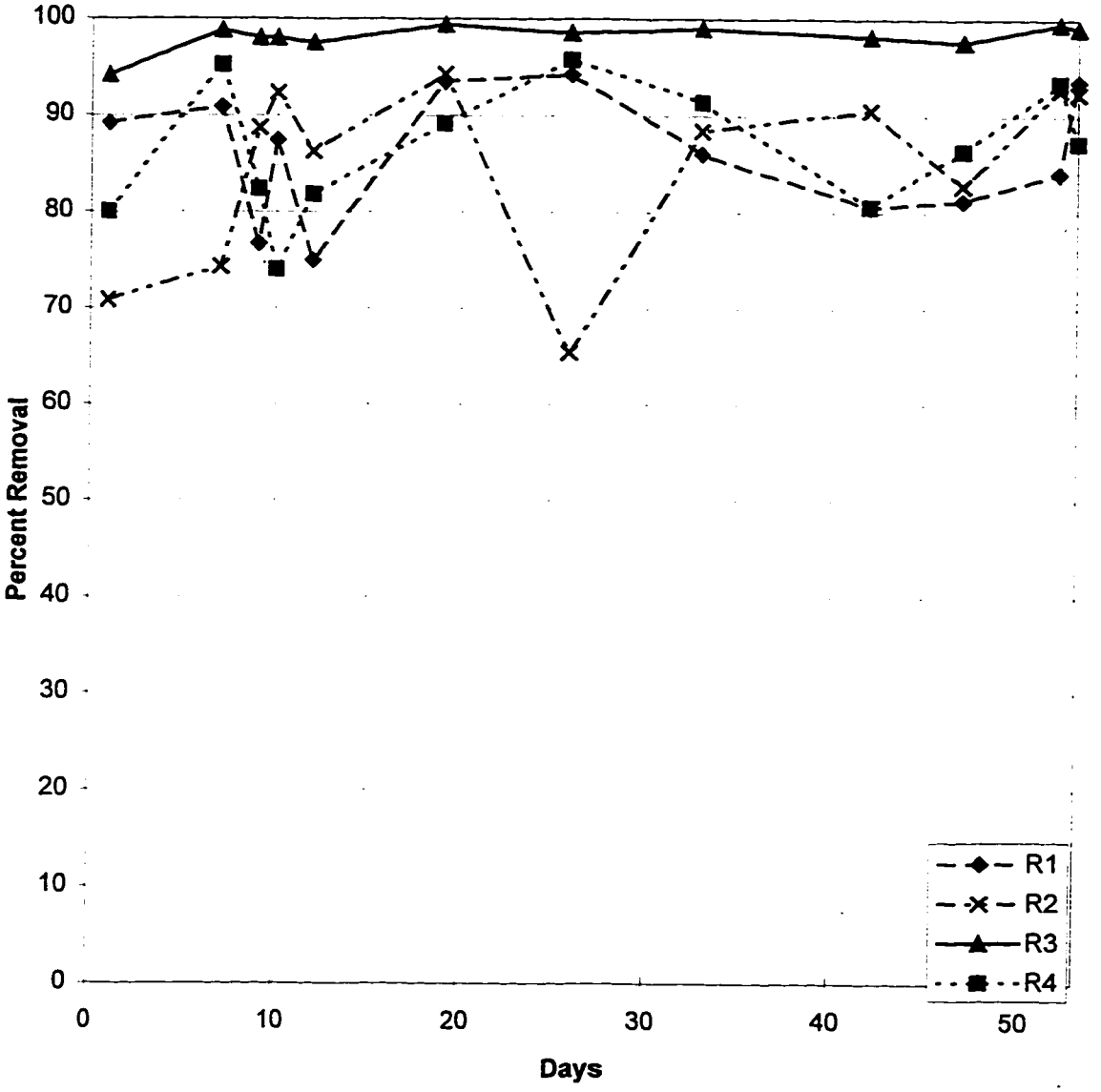


Fig 5.6 : Removals of Fecal Coliform During Phase I

from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.7. The corresponding fecal streptococcus removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.8.

5.2.5 Clostridium perfringens :

The *Clostridium perfringens* in the settled secondary effluent varied from $5.16x10^2$ to $2.3x10^1$, and averaged at $1.24x10^2$. After filtration in the control filter these were further reduced to range between $8.2x10^1$ to $2.0x10^0$, averaging at $2.73x10^1$, giving an average removal of 79%. Chlorination of the settled secondary effluent gave *Clostridium perfringens* in the range of $1.13x10^2$ to $8.0x10^0$, with an average at $5.32x10^1$. This implies an average removal of 44.5% due to chlorination alone. After filtration in the test filter these were further reduced to range between $3.2x10^1$ to $1.0x10^1$, and averaged at $1.2x10^1$. This represents an overall removal of 89.49% in the test filter. The variations in the *Clostridium perfringens* during Phase I in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.9. The corresponding *Clostridium perfringens* removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.10. The removals efficiencies of *Clostridium perfringens* in the control filter and in chlorination were very poor. This is due to the fact that Clostridium is a spore former and can survive harsh

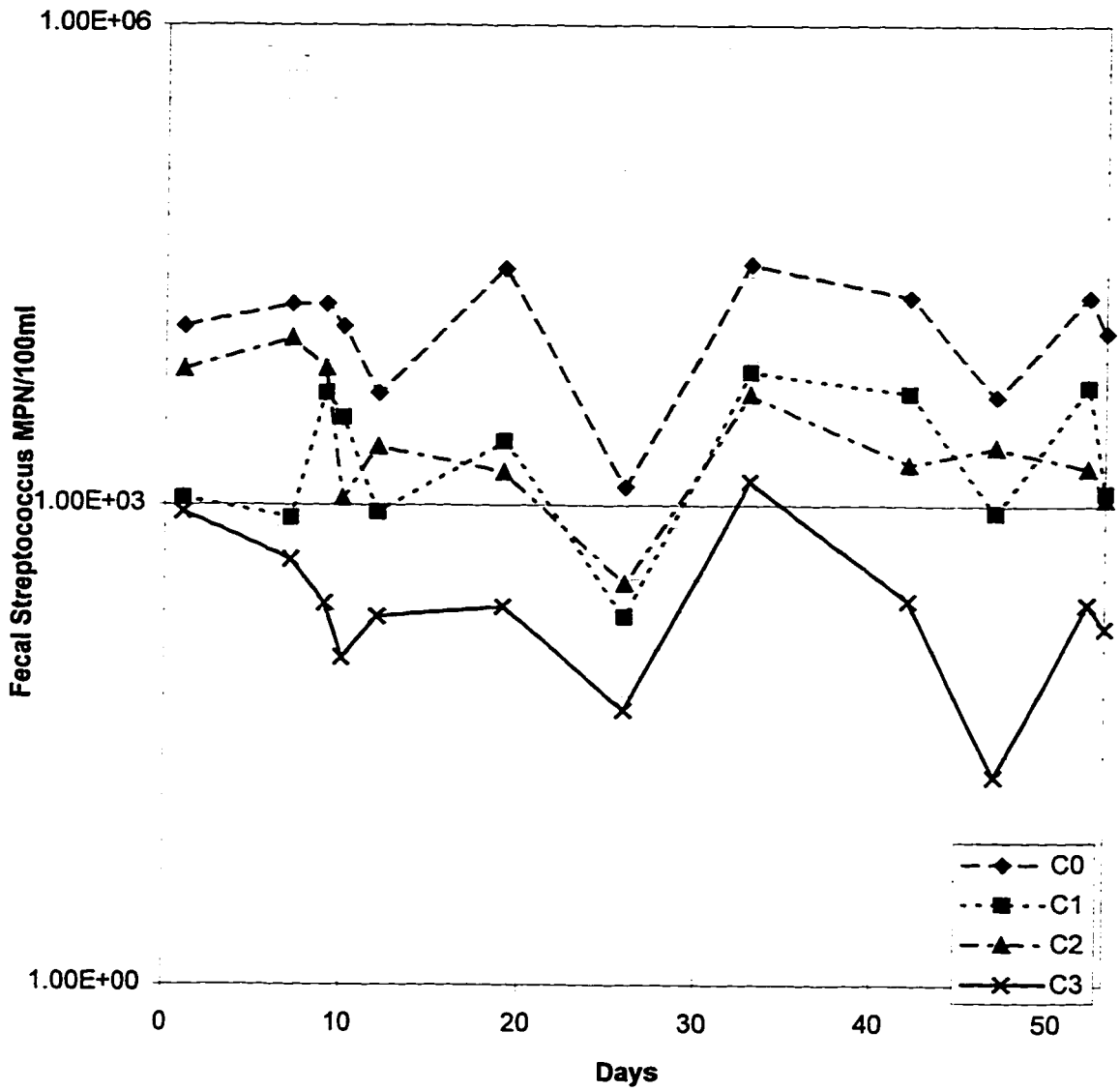


Fig 5.7 : Variation of Fecal Streptococcus During Phase I

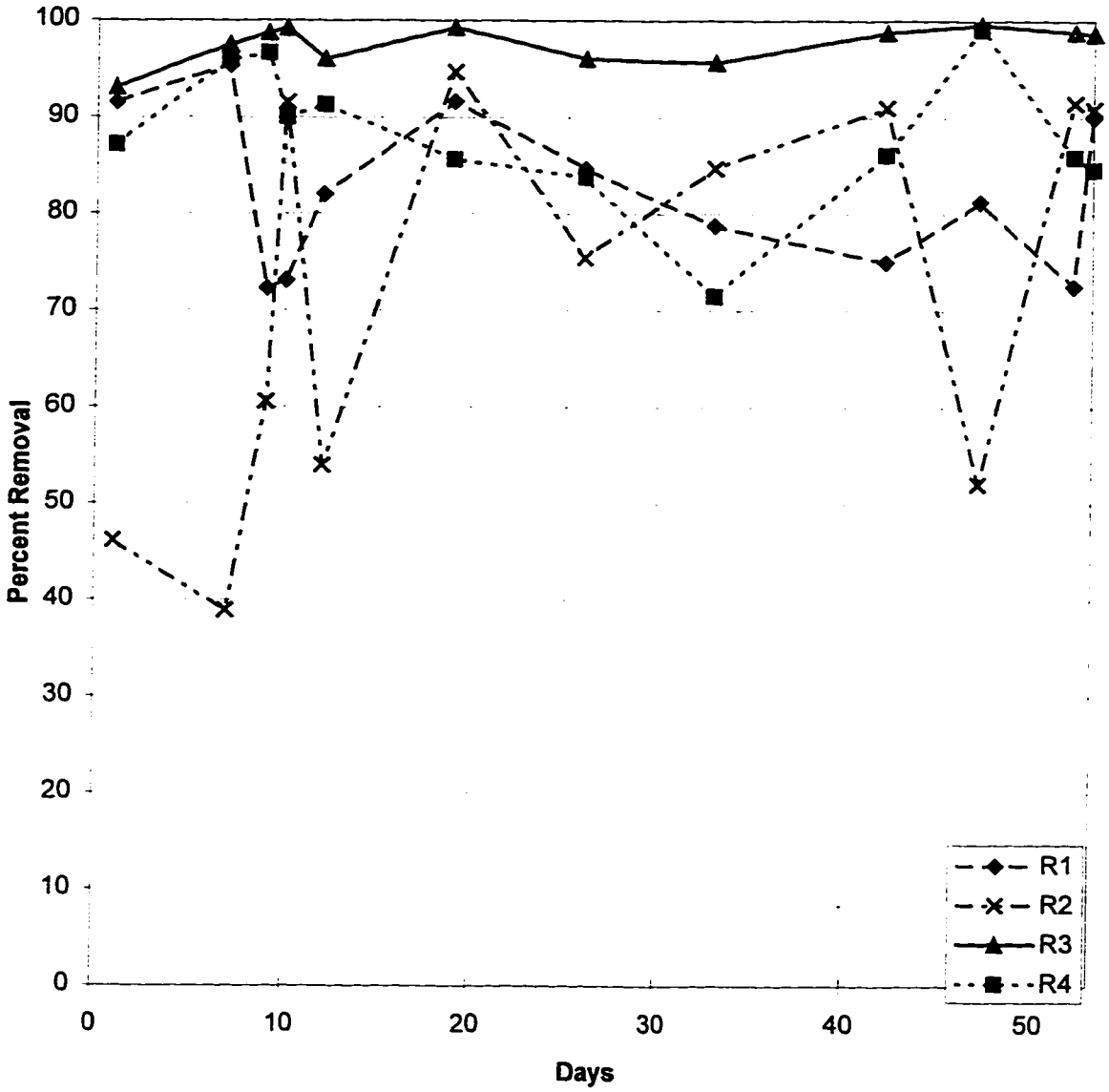


Fig 5.8 : Removal of Fecal Streptococcus During Phase I

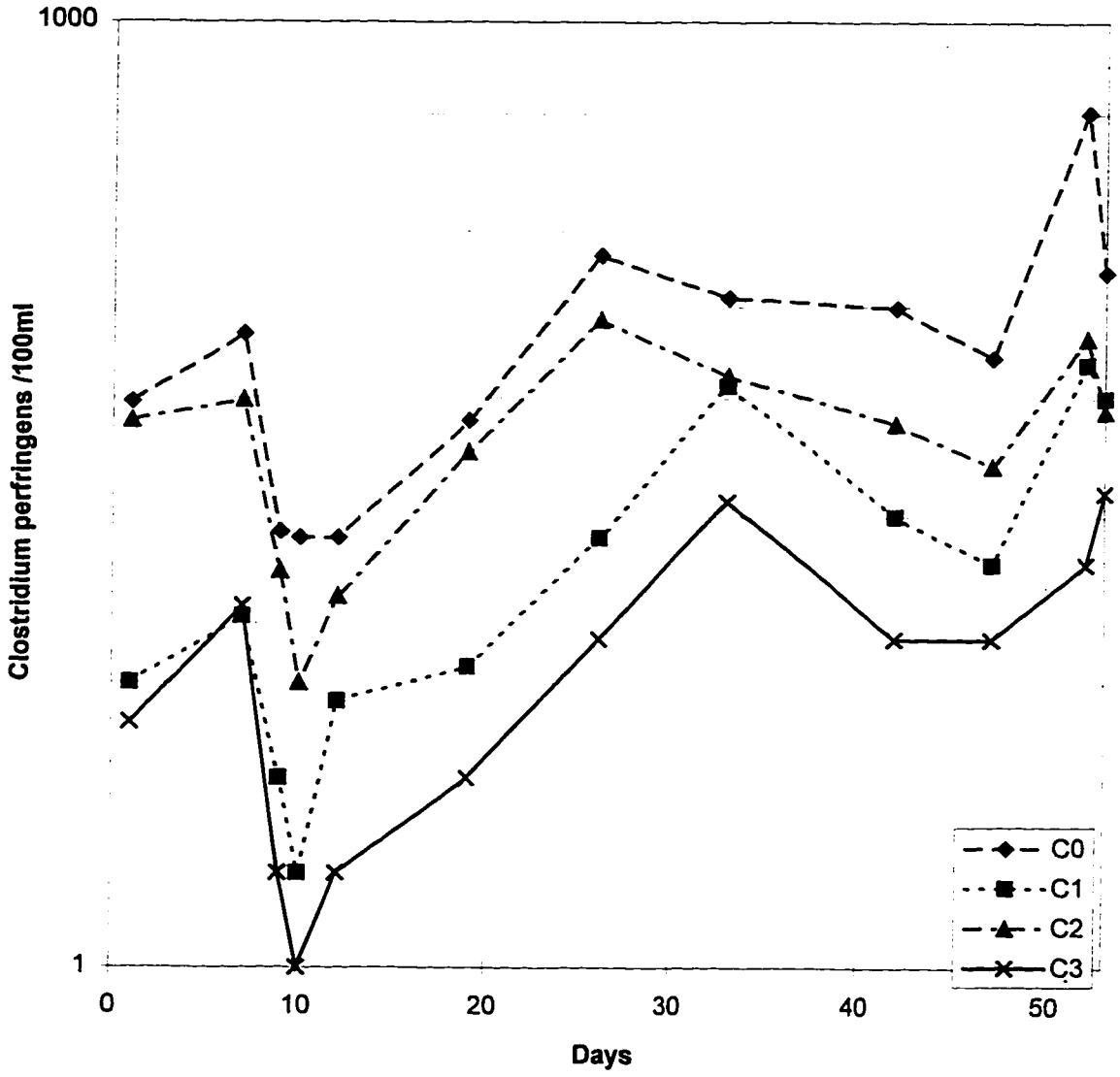


Fig 5.9 : Variation of *Clostridium perfringens* During Phase I

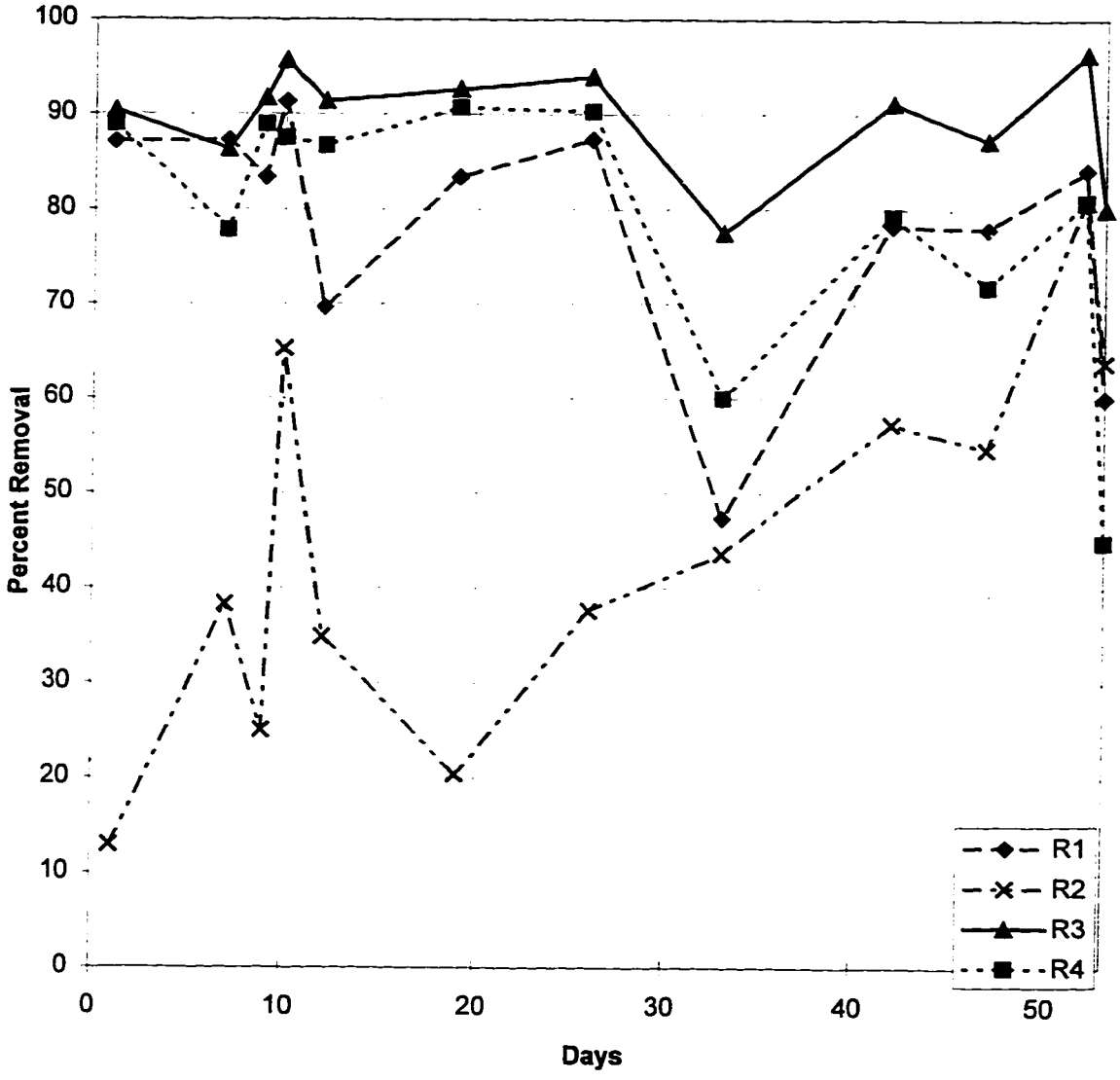


Fig 5.10 : Removal of *Clostridium perfringens* During Phase I

environments indefinitely. However a combined action of chlorination and filtration was effective in reducing the *Clostridium* counts effectively. The removal efficiencies in the control filter and in chlorination fluctuated greatly. This was also seen to some extent in the test filter, but this was not as great as those in the control filter.

5.2.6 Coliphage :

The coliphage count in the settled secondary effluent varied from $2.42x10^3$ to $3.4x10^2$ and averaged at $7.7x10^2$. After filtration in the control filter these were further reduced to range between $8.0x10^2$ to $3.0x10^1$, averaging at $1.82x10^2$. This gives an average removal of 80.1% in the control filter. After chlorination of the settled secondary effluent, the coliphage were reduced to the range between $7.0x10^2$ to $1.12x10^2$, and averaged at $3.37x10^2$, giving an average removal of 49.1%. After filtration in the test filter, the coliphage varied from $4.2x10^2$ to $1.0x10^0$, and averaged at $8.82x10^1$. This gives an overall removal of 91.31%. The variations in the coliphage during Phase I in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.11. The corresponding coliphage removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.12.

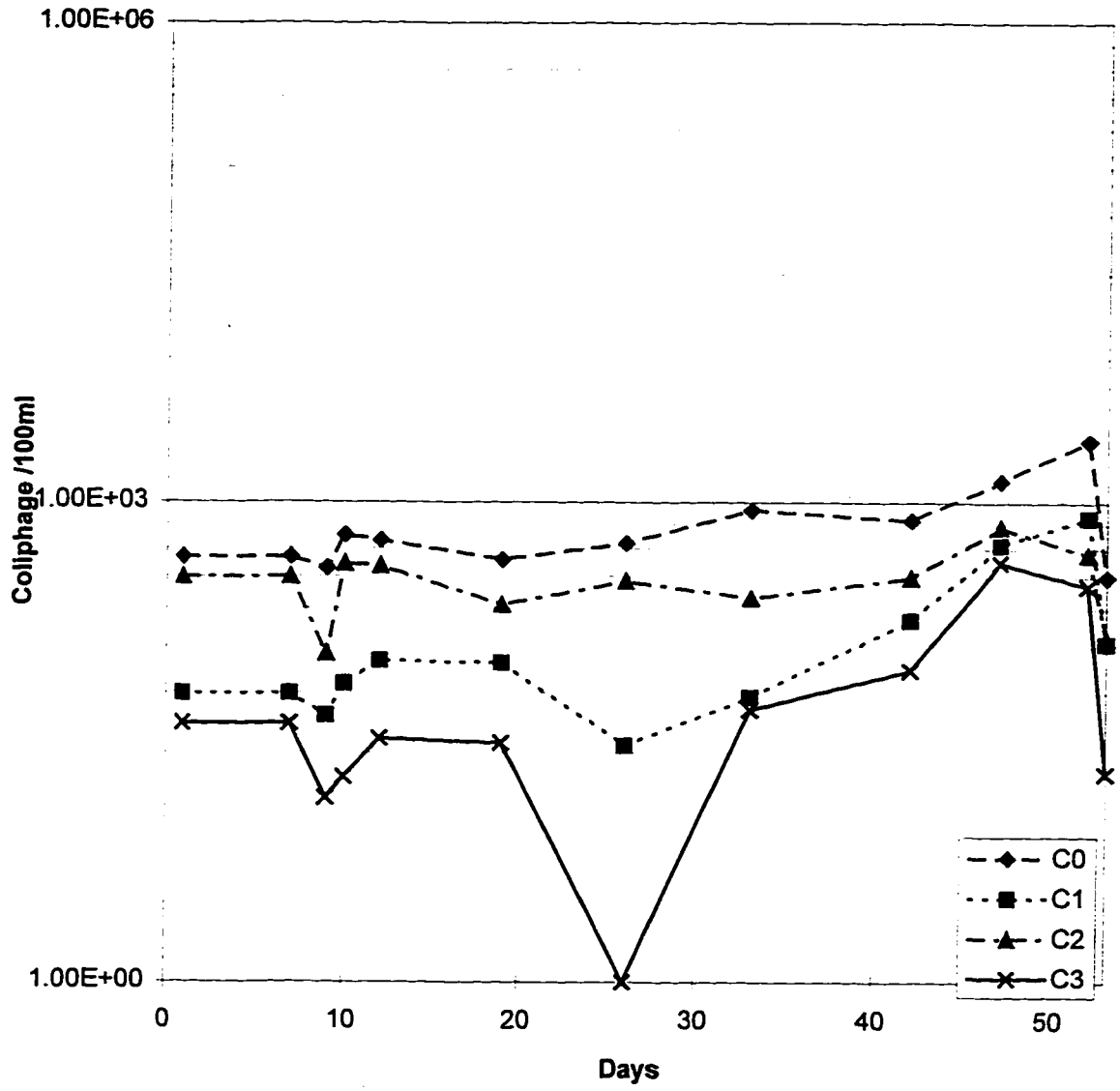


Fig 5.11 : Variation of Coliphage During Phase I

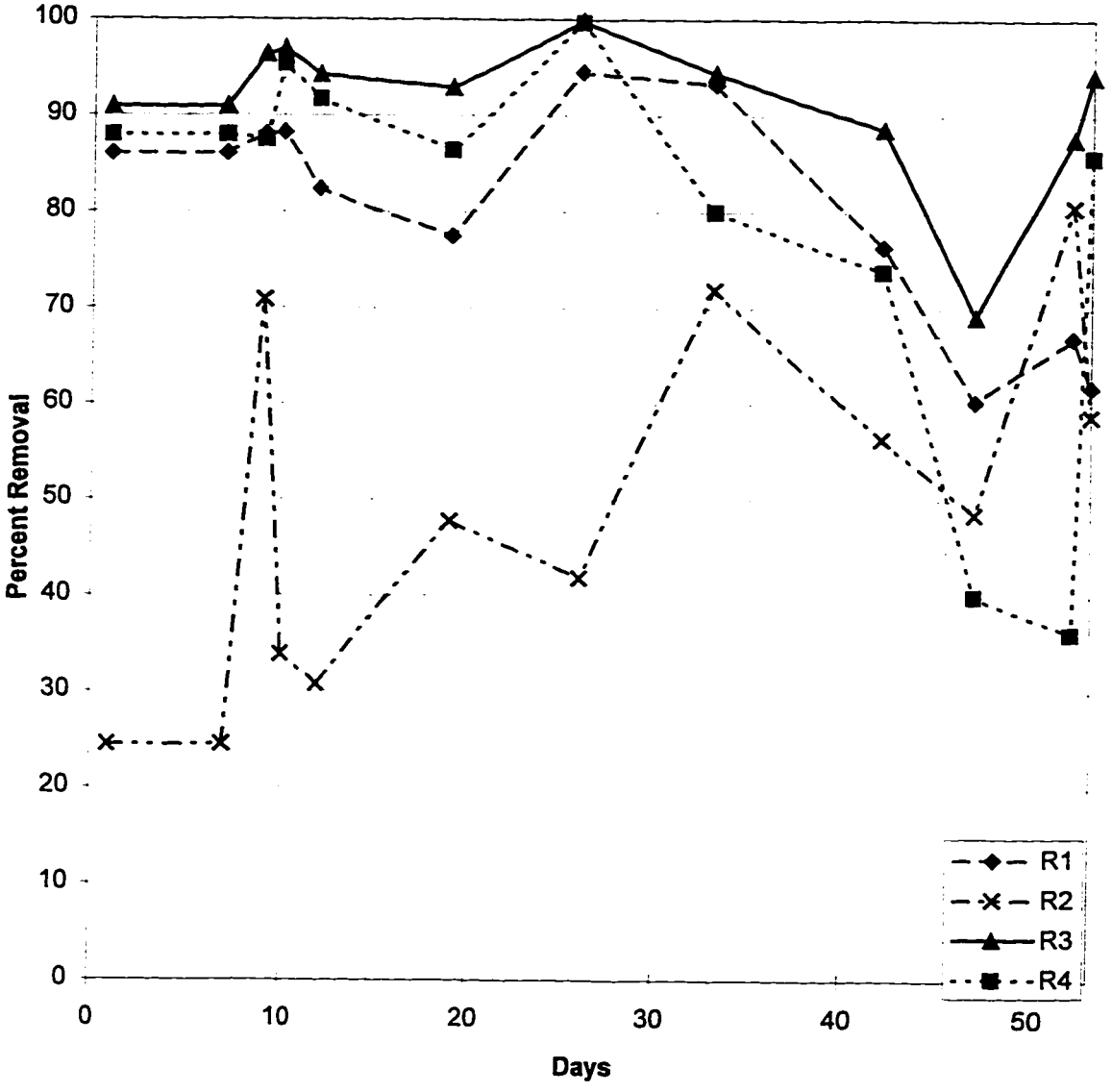


Fig 5.12 : Removal of Coliphage During Phase I

5.3 Phase II : Chlorine dose of 15 mg/l

5.3.1 Standard Plate Count :

During the second phase of the study, standard plate counts in the settled secondary effluent varied from $6.25x10^4$/ml to $4.2x10^3$/ml, with an average around $2.55x10^4$. After filtration in the control slow sand filter these were reduced to $5.2x10^3$ to $5.8x10^2$ with an average of $2.04x10^3$. This represents an average removal of 89.9% in the control filter. After chlorination with a chlorine dose of 15 mg/l, the standard plate count ranged from $4.2x10^1$ to $1.0x10^1$ with an average around $2.91x10^1$, representing an average reduction of 99.74% by chlorination alone. After filtration in the test filter, these were further reduced to range between $6.0x10^0$ to $3.0x10^0$ and averaged at $4.2x10^0$ representing an overall removal of 99.96%. The variations in the standard plate count during Phase II in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.13. The corresponding standard plate count removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.14. These standard plate count removals were substantiated by the various studies involving slow sand filtration of secondary effluents [Ellis, 1985; Farooq *et al.*, 1993a,1993b]. Farooq *et al.* [1993b], have reported removal of

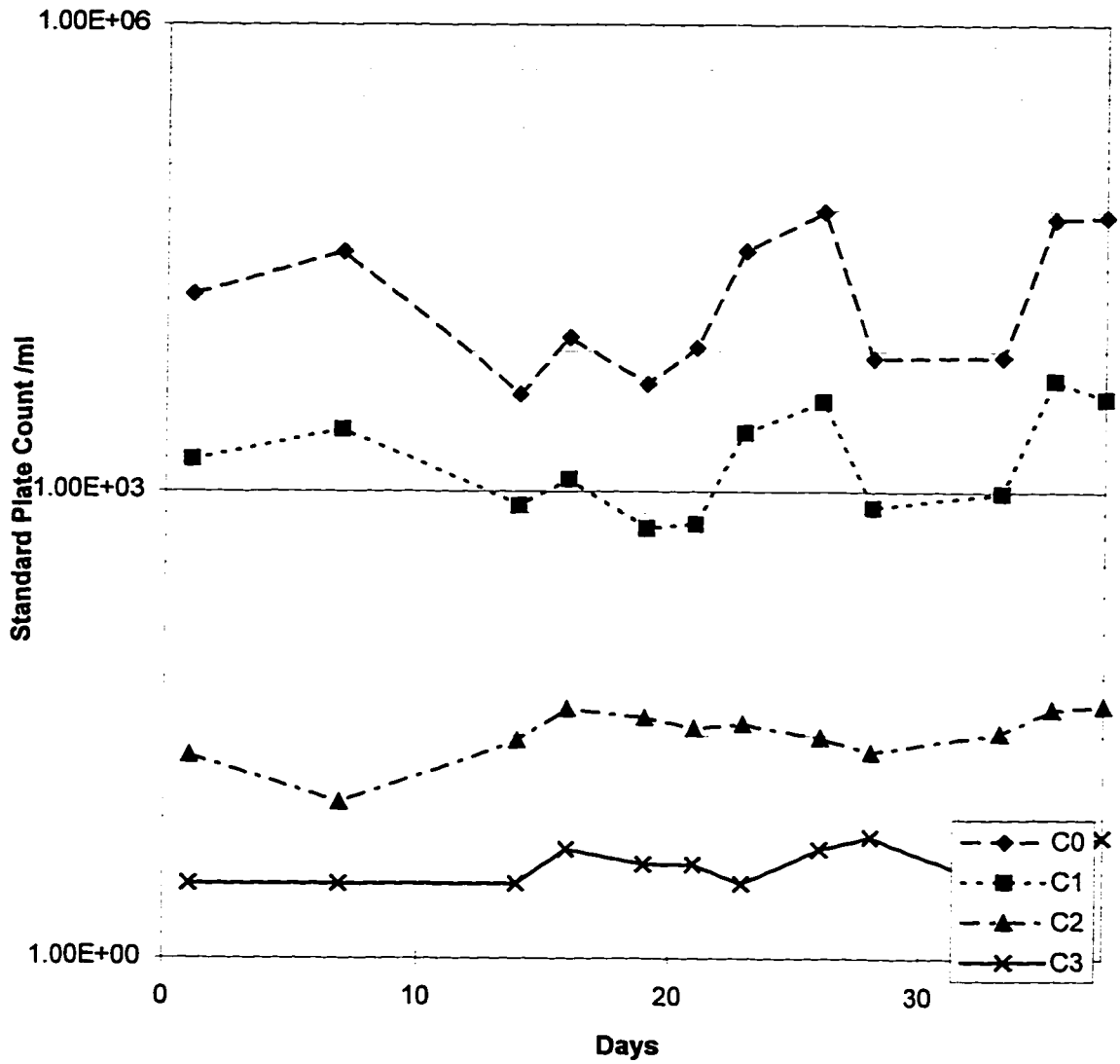


Fig 5.13 : Variation of Standard Plate Count During Phase II

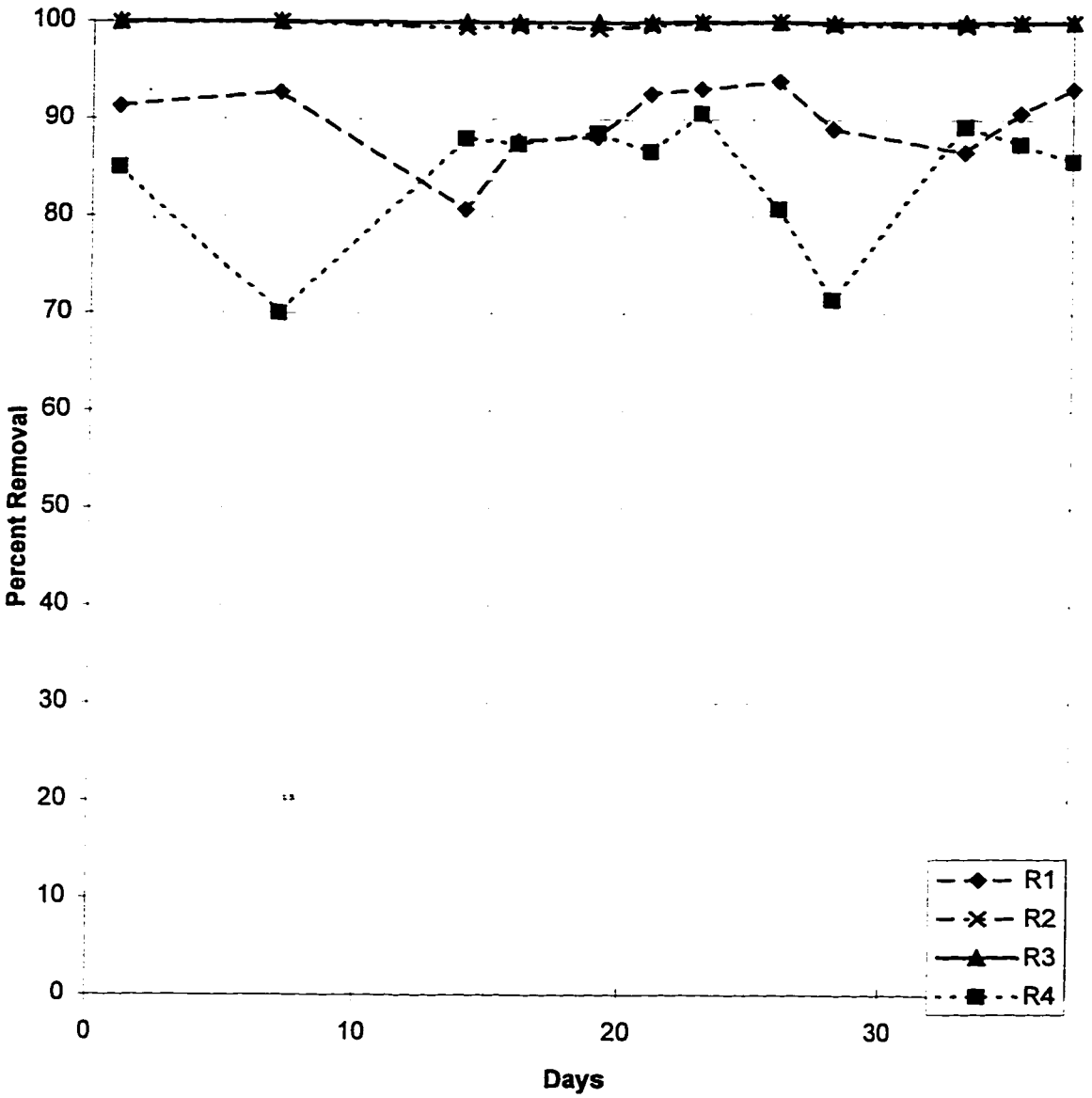


Fig 5.14 : Removal of Standard Plate Count During Phase II

standard plate counts and coliforms in the range 88-93%, in slow sand filtration using chlorinated secondary effluent, which was stored for a period of 5 days prior to treatment. This could be the reason for the comparatively lower removals reported. Another reason for this difference could be the action of chlorine even as the water is being filtered in the slow sand filter.

5.3.2 Total Coliform:

The total coliforms in the settled secondary effluent ranged from $1.7x10^5$ to $6.0x10^4$ and averaged at $1.17x10^5$. The total coliforms in the effluent from the control filter ranged from $3.3x10^4$ to $6.2x10^4$ averaging around $2.19x10^4$. The average removals in the control filter being 81.68%. Chlorination of the settled secondary effluent reduced the total coliforms to the range of $1.2x10^2$ to $4.0x10^1$ with an average of $7.42x10^1$. This gives an average removal of 99.93% by chlorination alone. After filtration in the test slow sand filter, the total coliforms ranged between $1.3x10^1$ to $2.0x10^0$, averaging at $6.42x10^0$. Thus the overall removal of total coliforms was 99.994%. The variations in the total coliform during Phase II in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.15. The corresponding total coliform removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.16.

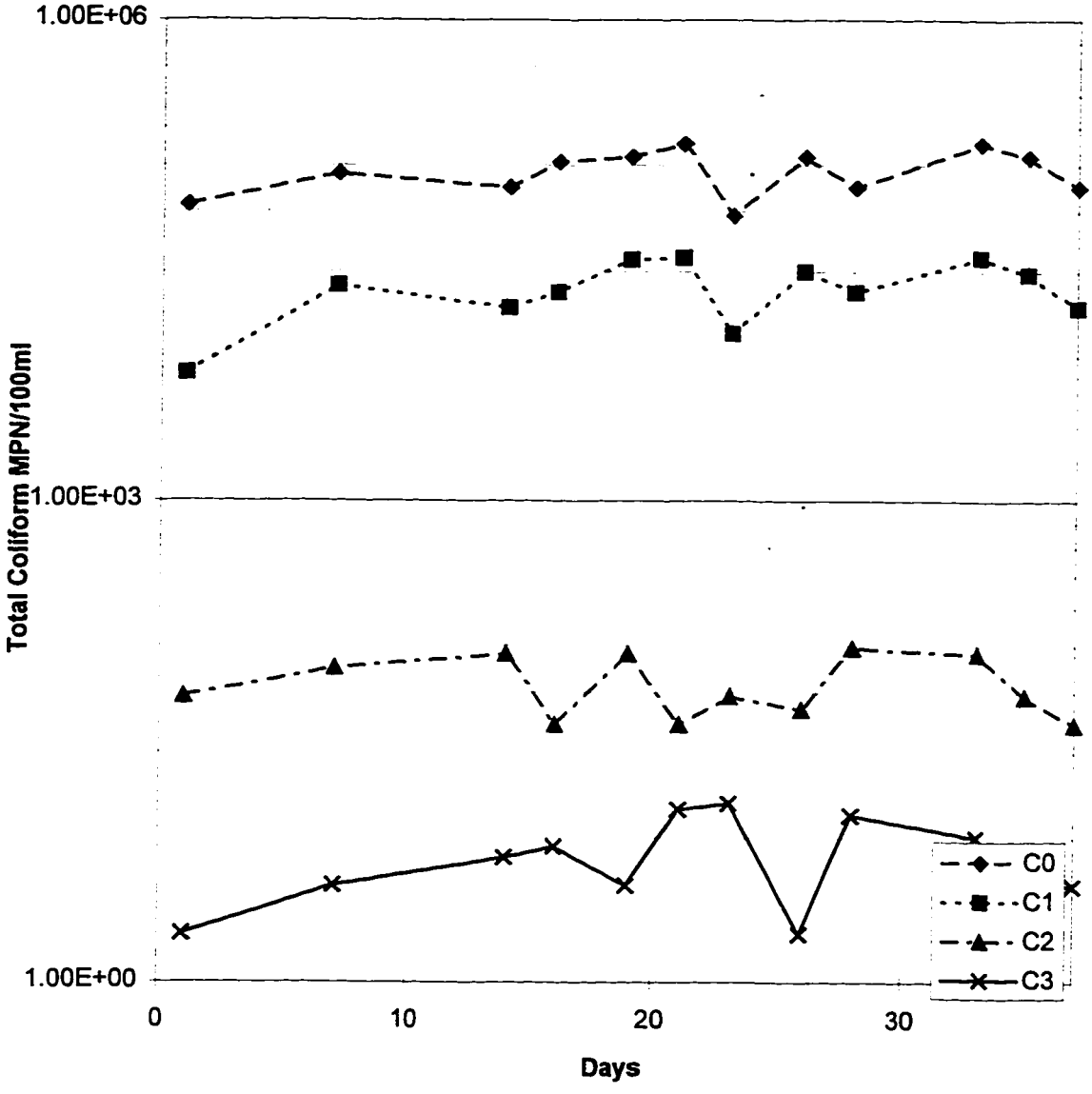


Fig 5.15 : Variation of Total Coliform During Phase II

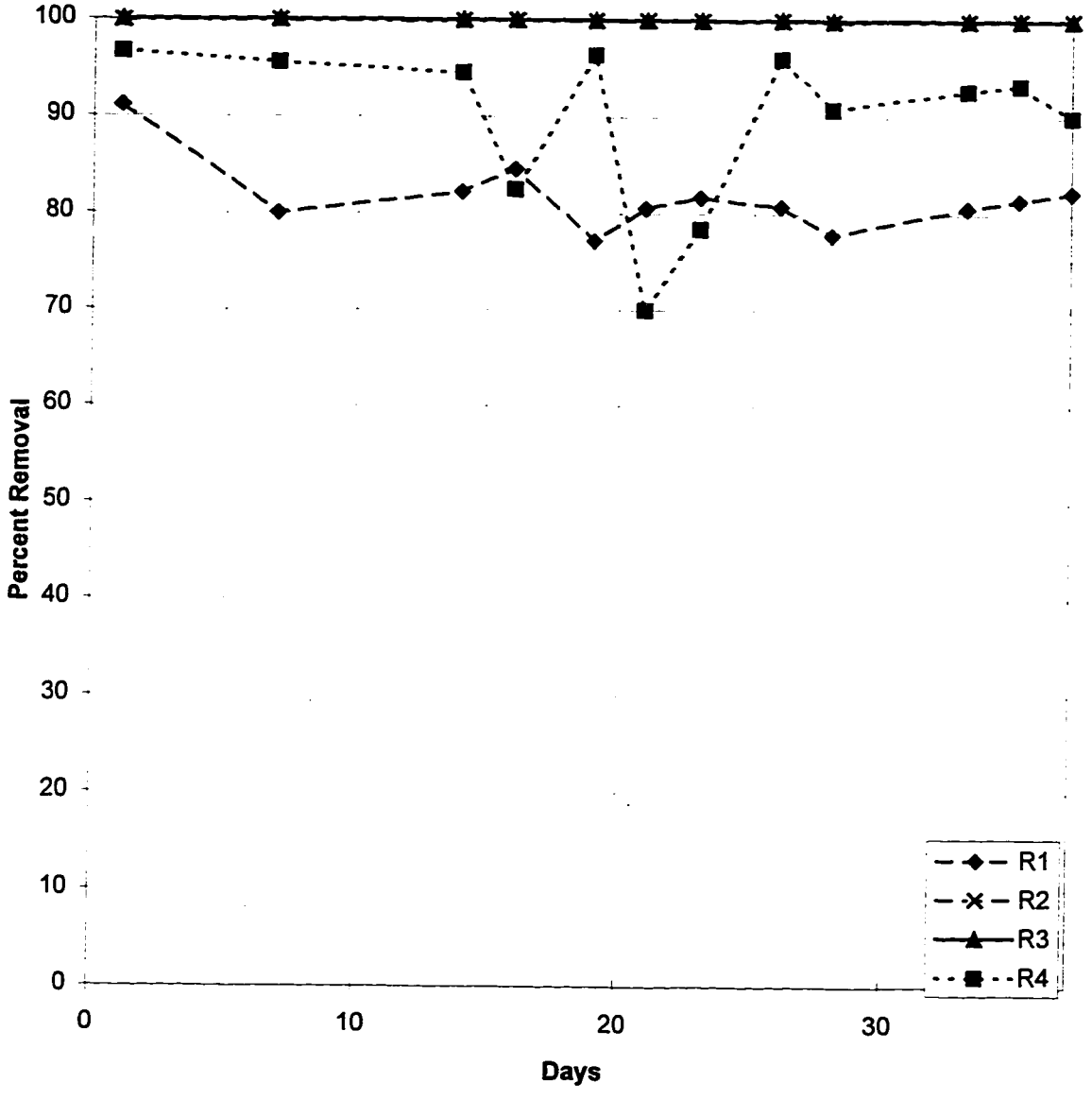


Fig 5.16 : Removal of Total Coliform During Phase II

The total coliforms are the most widely used indicator organisms. This is partly because its detection and enumeration are standardized and because of the fact that most microbial standards recognize coliforms as an indicator of fecal pollution. However there were large fluctuations in the removal efficiencies in the control filter. This is typical of slow sand filters treating secondary effluents. Prechlorination of the influent resulted in a better and more reliable coliform removal.

5.3.3 Fecal Coliform :

In the second phase of the study, the fecal coliform in the settled secondary effluent ranged from $1.4x10^5$ to $3.5x10^4$ and averaged at $8.96x10^4$. After filtration in the control filter, these were reduced to in the range of $3.3x10^4$ to $2.6x10^3$ with an average at $1.67x10^4$, representing an average removal of 86.44%. Chlorination of the settled secondary effluent yielded fecal coliform in the range of $7.0x10^1$ to $1.6x10^1$ and averaged at $3.59x10^1$, giving an average removal of 99.95%. Filtration in the test filter further reduced the fecal coliform to range between $7.0x10^0$ to $1.0x10^0$ and averaged at $3.58x10^0$, giving an overall average removal of 99.995%. The variations in the fecal coliform during Phase II in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig

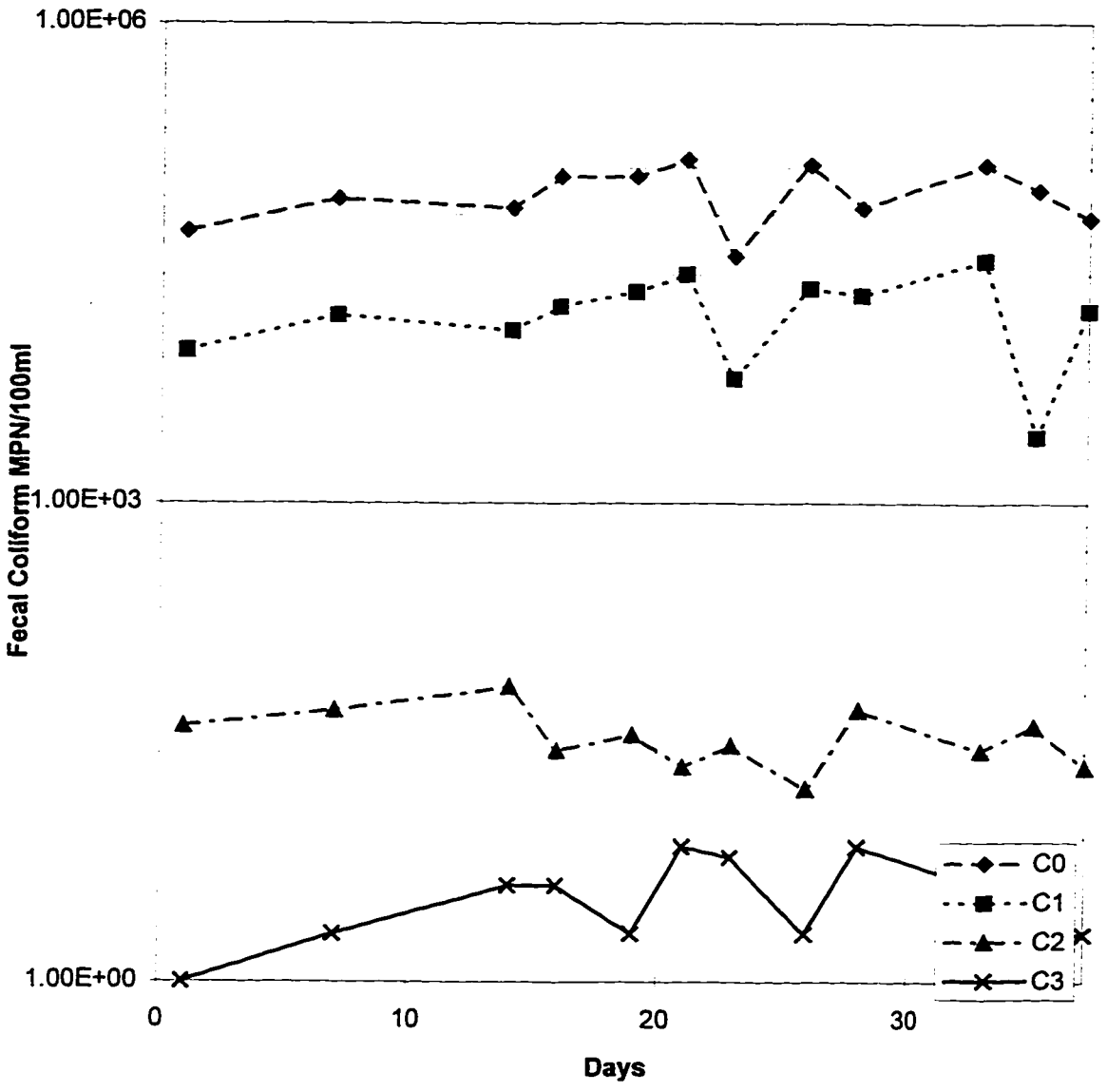


Fig 5.17 : Variation of Fecal Coliform During Phase II

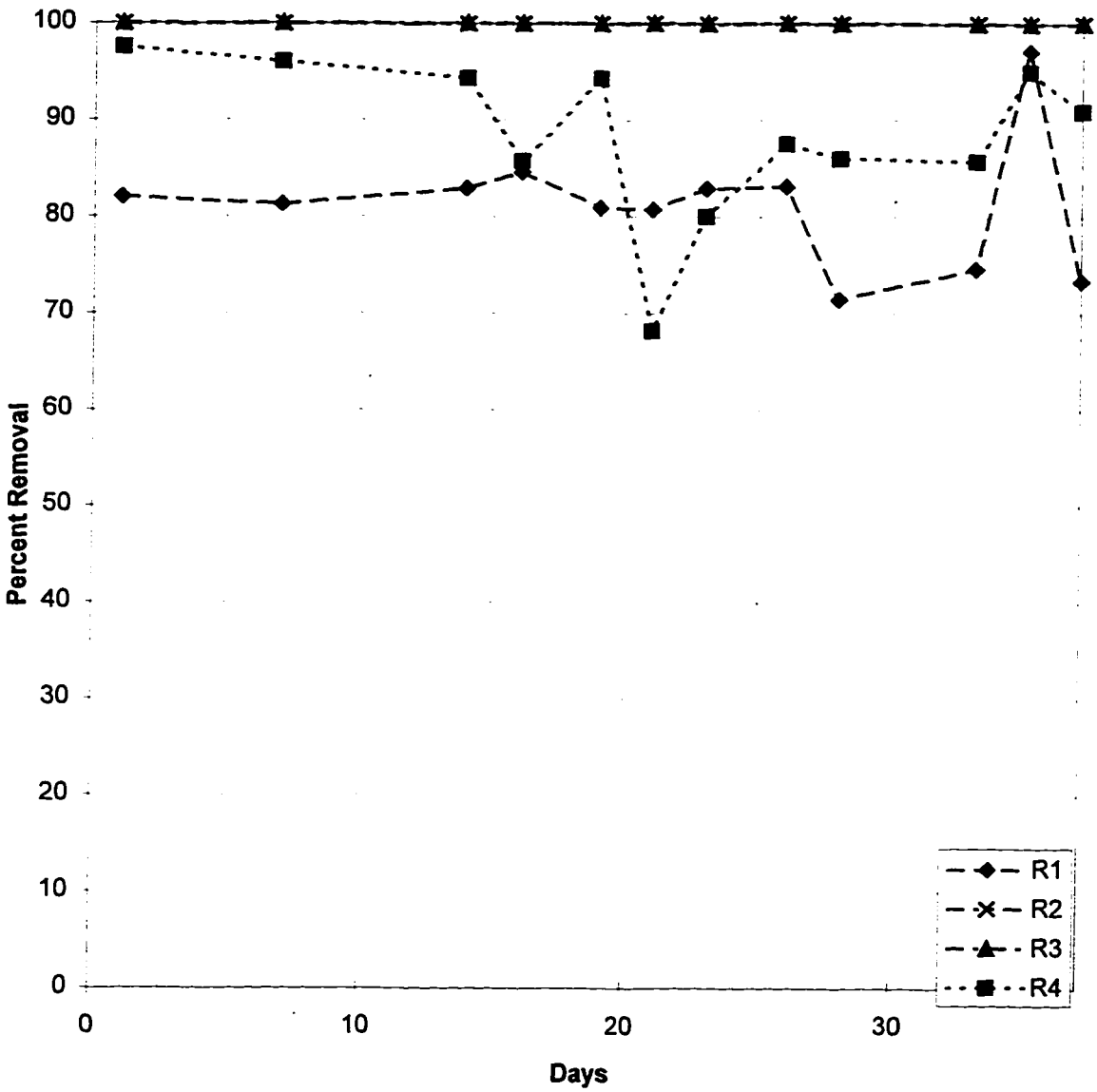


Fig 5.18 : Removal of Fecal Coliform During Phase II

5.17. The corresponding fecal coliform removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.18.

Fecal coliforms are the thermotolerant coliforms capable of tolerating elevated temperatures. The removal efficiencies fluctuated widely in the control filter. However due to prechlorination in the test filter these fluctuations were greatly controlled. Thus prechlorination can be beneficial in the coliform removals in slow sand filtration. Studies by Cleasby *et al.* [1984], have reported coliform removals above 99%. These high removals were due to the fact that the water being treated was spiked water with very low coliform counts.

5.3.4 Fecal Streptococcus :

The fecal streptococcus in the settled secondary effluent ranged between $3.2x10^4$ to $2.6x10^3$ and averaged at $7.55x10^3$. After filtration in the control filter these were reduced to the range of $1.4x10^3$ to $4.0x10^2$ and averaged at $7.67x10^2$. This implies a removal of 87.1% in the control filter. Chlorination of the settled secondary effluent yielded fecal streptococcus in the range of $1.1x10^1$ to $4.0x10^0$ and averaging at $8.67x10^0$, resulting in a removal of 99.81% due to chlorination alone. After filtration in the test filter the fecal streptococcus ranged between $4.0x10^0$ to $1.0x10^0$ and averaged at $2.08x10^0$, giving an average overall removal of 99.998%. The variations in the

fecal streptococcus during Phase II in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.19. The corresponding fecal streptococcus removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.20. Fecal streptococcus is the least documented of the indicator organisms with regard to slow sand filtration. However it has been found to be an effective indicator of fecal pollution in adverse environments. This makes it important in studies involving the disinfection of waters. The position of fecal streptococci is intermediate between the coliphages and the thermotolerant (fecal) coliforms. [Havelaar and Nieuwstad, 1985]. This is also reflected in the present study which found fecal streptococcus to be more resistant than coliforms and less resistant than coliphage in chlorination.

5.3.5 Clostridium perfringens :

The *Clostridium perfringens* in the settled secondary effluent varied from $4.0x10^2$ to $1.2x10^2$, and averaged at $2.85x10^2$. After filtration in the control filter these were further reduced to range between $9.0x10^1$ to $3.0x10^1$, averaging at $5.62x10^1$, giving an average removal of 80%. Chlorination of the settled secondary effluent gave *Clostridium perfringens* in the range of $2.2x10^2$ to $1.2x10^1$, with an average at $7.18x10^1$. This implies an average removal of 71.35% due to chlorination alone. After filtration in the test filter

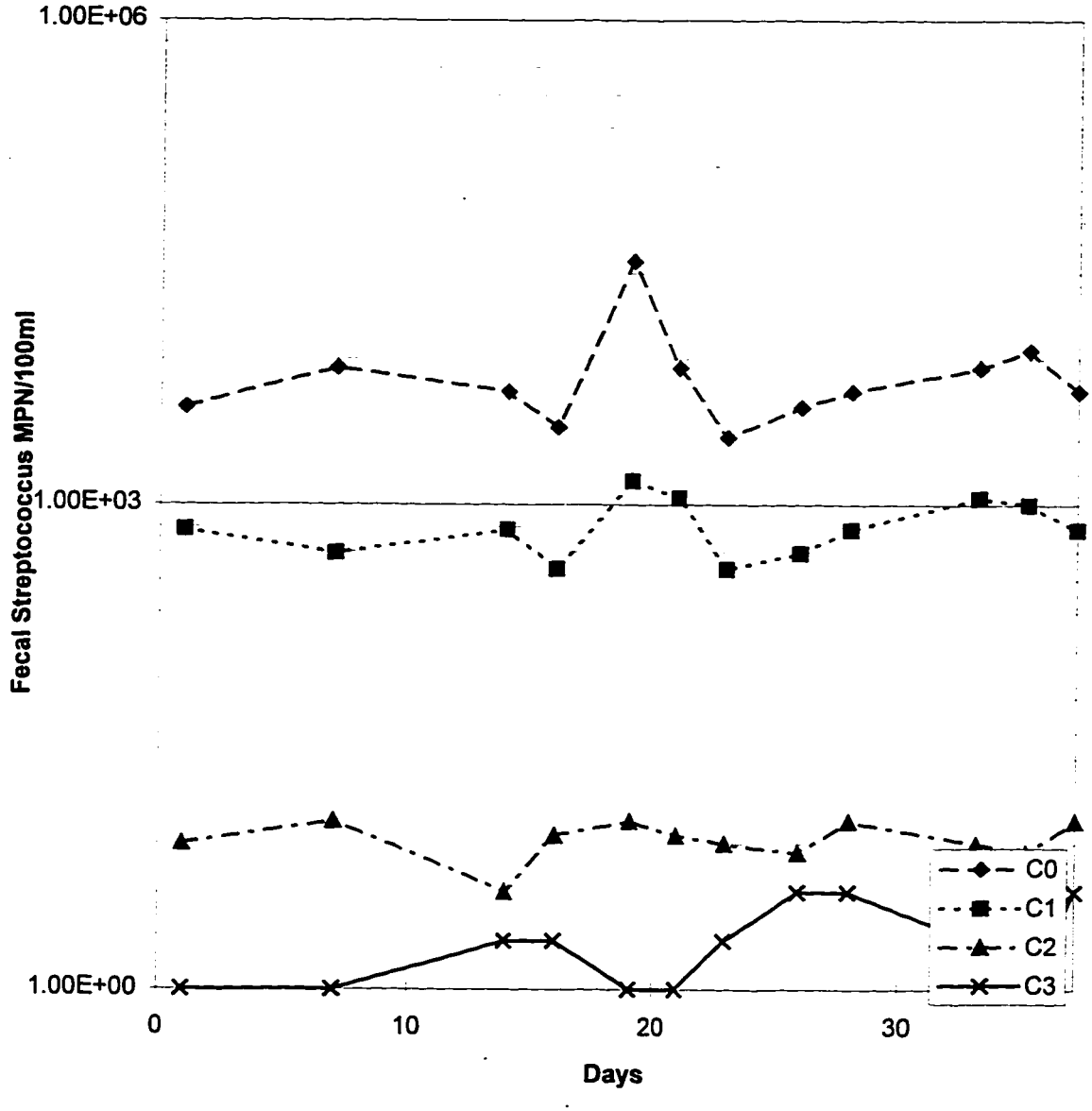


Fig 5.19 : Variation of Fecal Streptococcus During Phase II

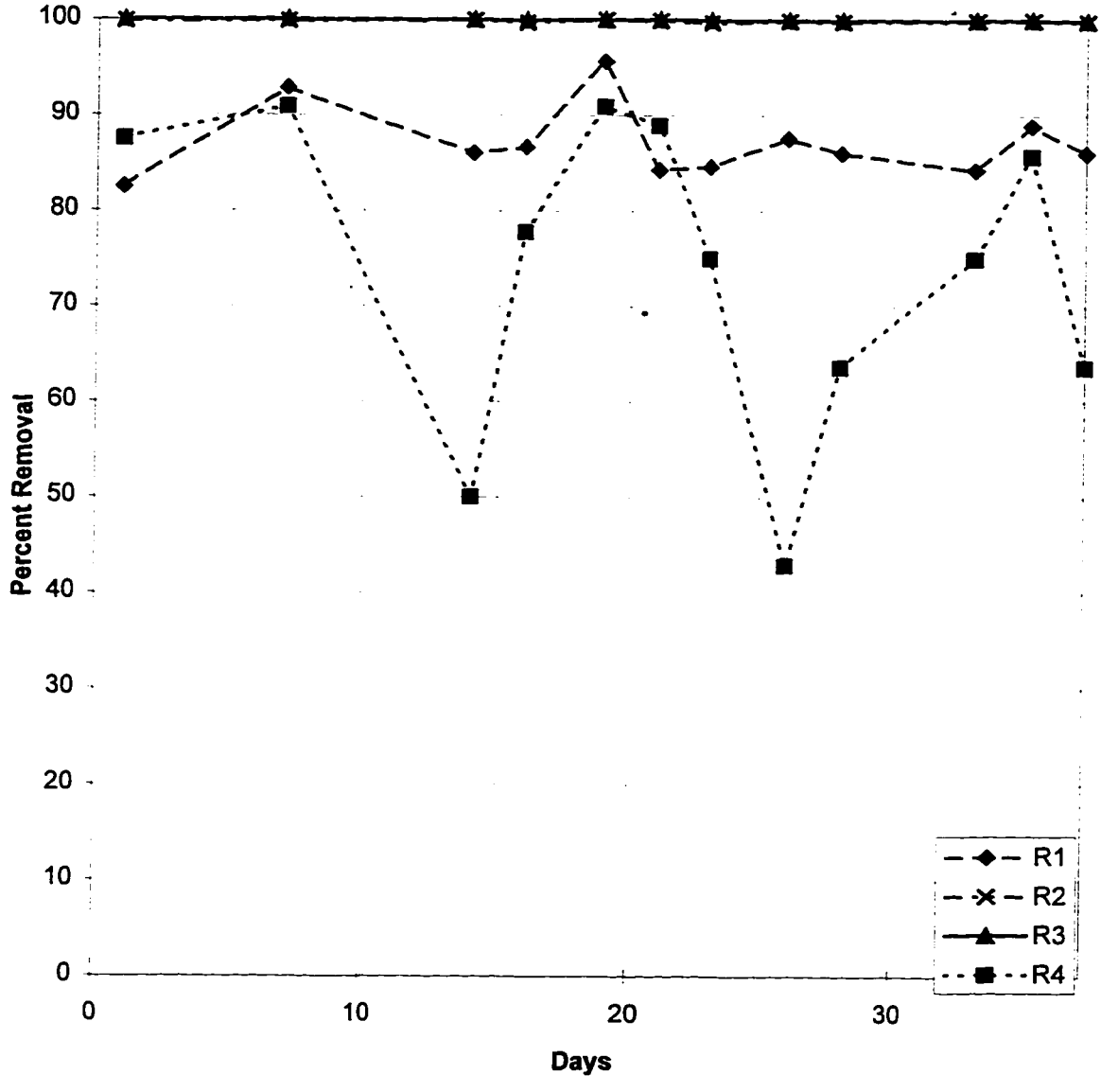


Fig 5.20 : Removal of Fecal Streptococcus During Phase II

these were further reduced to range between $8x10^0$ to $1.0x10^0$, and averaged at $8.82x10^1$. This represents an overall removal of 92.3% in the test filter. The variations in the *Clostridium perfringens* during Phase II in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.21. The corresponding *Clostridium perfringens* removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.22.

Clostridium perfringens was by far the most resistant microbial indicator with removals of 44.5% and 71% in phase I and II respectively. Its ability to form spores is a major reason for its resistance. Studies by Havelaar and Nieuwstad [1985], have shown that *Cl. Perfringens* is not significantly reduced even with chlorine dose of 5 mg/l and chlorine residuals of 4 mg/l. Hirata *et.al.* [1991], on the basis of their studies involving laboratory cultured and indigenous *Cl. perfringens* cells have found that the indigenous cells were more resistant to any form of treatment by a factor of 3 to 5 times. They observed that *Cl. perfringens* was the least reduced in all the unit processes including chlorination. However slow sand filtration proves effective in removing this indicator. Again it is interesting to note that the combined action of chlorination and filtration is more effective in removing *Cl. Perfringens* than either process alone.

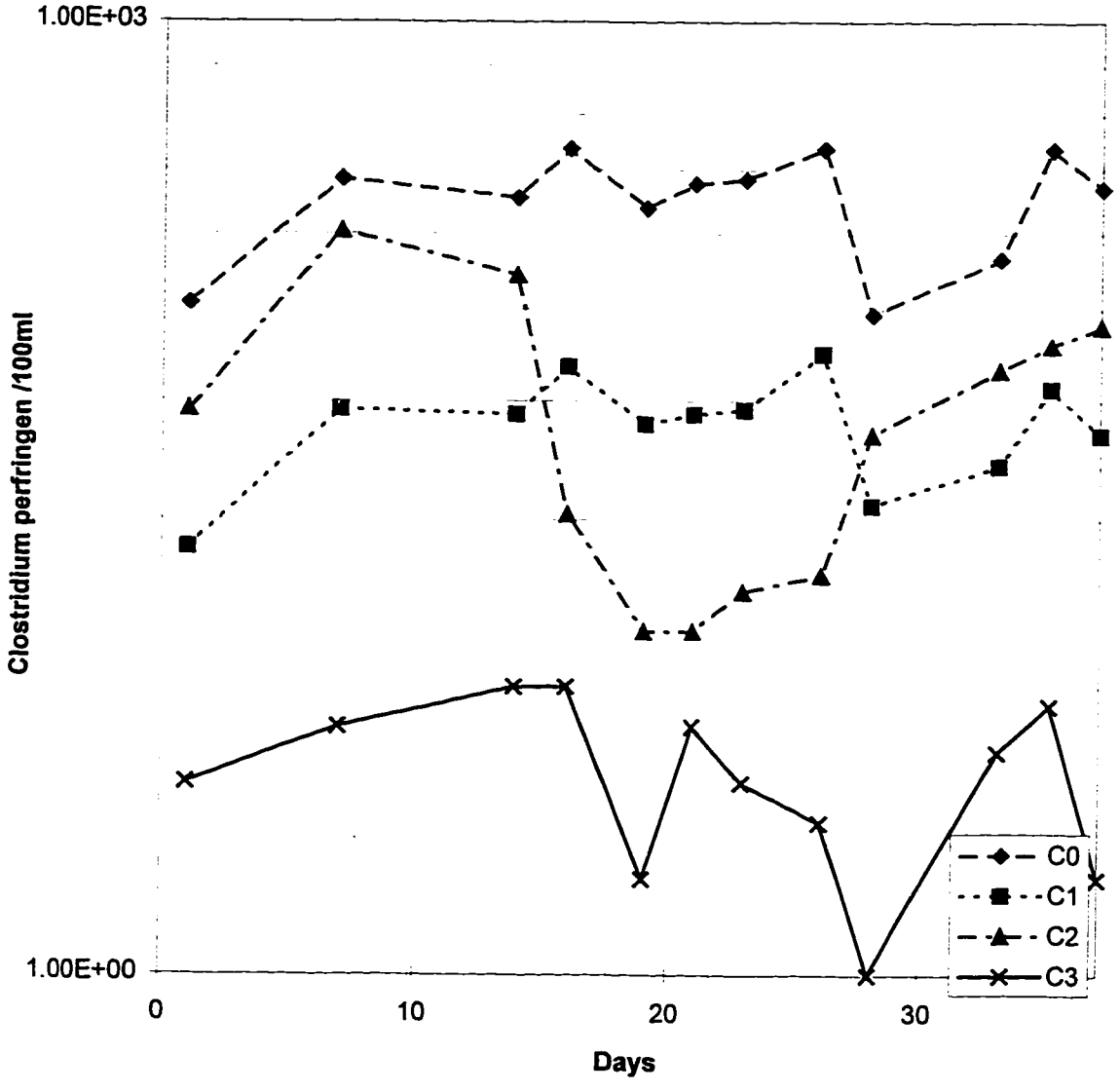


Fig 5.21 : Variation of *Clostridium perfringens* During Phase II

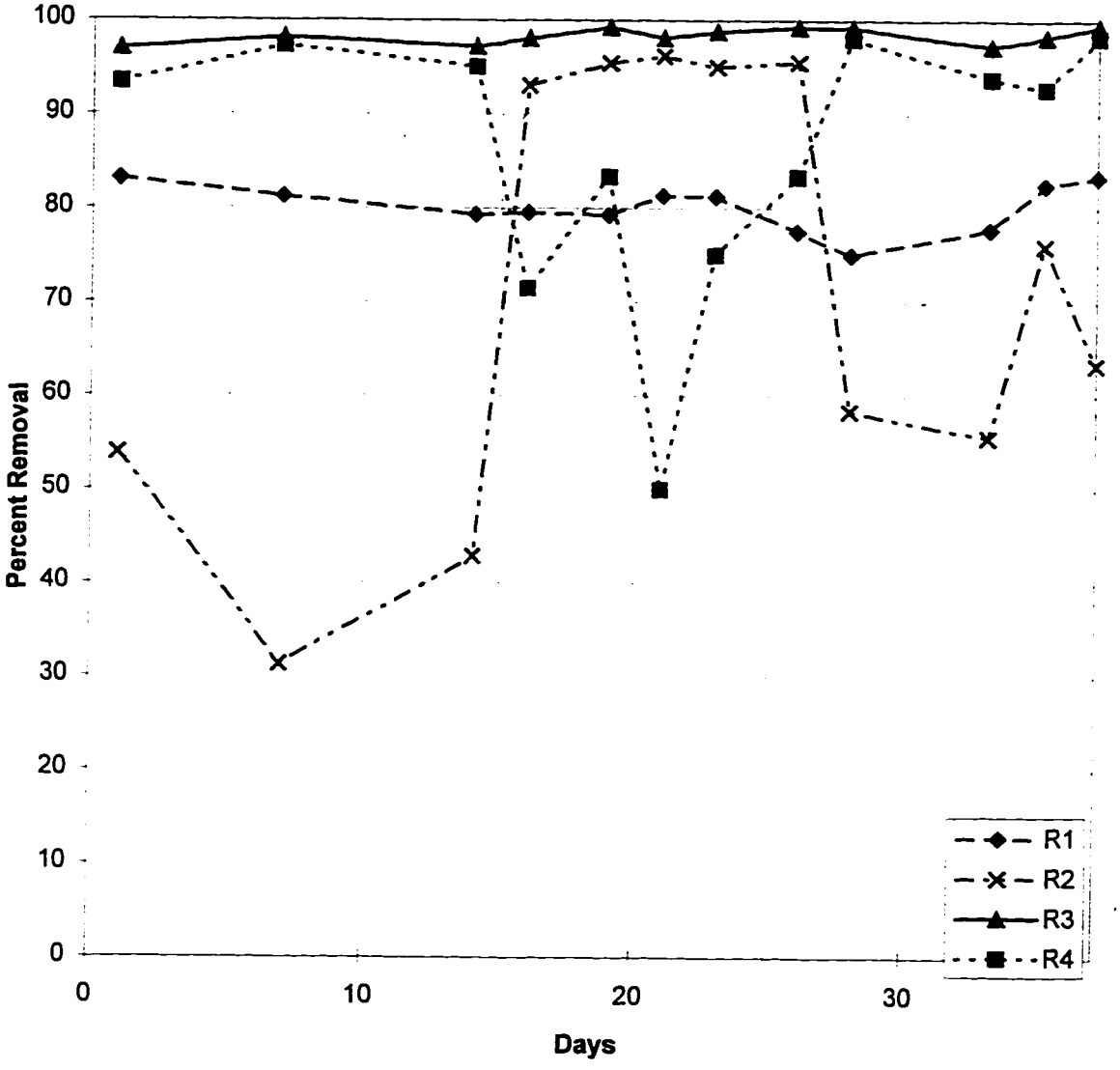


Fig 5.22 : Removal of *Clostridium perfringens* During Phase II

5.3.6 Coliphage :

The coliphage count in the settled secondary effluent varied from $2.0x10^3$ to $3.0x10^2$ and averaged at $9.92x10^2$. After filtration in the control filter these were further reduced to range between $3.7x10^2$ to $1.1x10^1$, averaging at $1.73x10^2$. This gives an average removal of 82.7% in the control filter.

After chlorination of the settled secondary effluent, the coliphage were reduced to the range between $6.0x10^2$ to $8x10^1$, and averaged at $3.02x10^2$, giving an average removal of 70.6%. After filtration in the test filter, the coliphage varied from $7.0x10^0$ to $1.0x10^0$, and averaged at $3.75x10^0$. This gives an overall removal of 99.55%. The variations in the coliphage during Phase II in the settled secondary effluent, effluent from control and test filter, and chlorinated settled secondary effluent are shown in Fig 5.23. The corresponding coliphage removals due to chlorination and filtration in the control and test filters are shown in Fig. 5.24.

In a study involving the chlorination efficiency of coliphages, Kott *et al.* [1973], have reported that coliphages were by far the most resistant to disinfection. 43 to 38% of f2 coliphages were recovered even after a chlorine dose of 80 mg/l and contact times of 2 hr, leading to the conclusion that the coliphage group consists of some very resistant strains. This leads to the premise that the coliphages detected in the in the test filter effluents may be the more resistant strains of coliphage. Assuming the coliphage to enteric

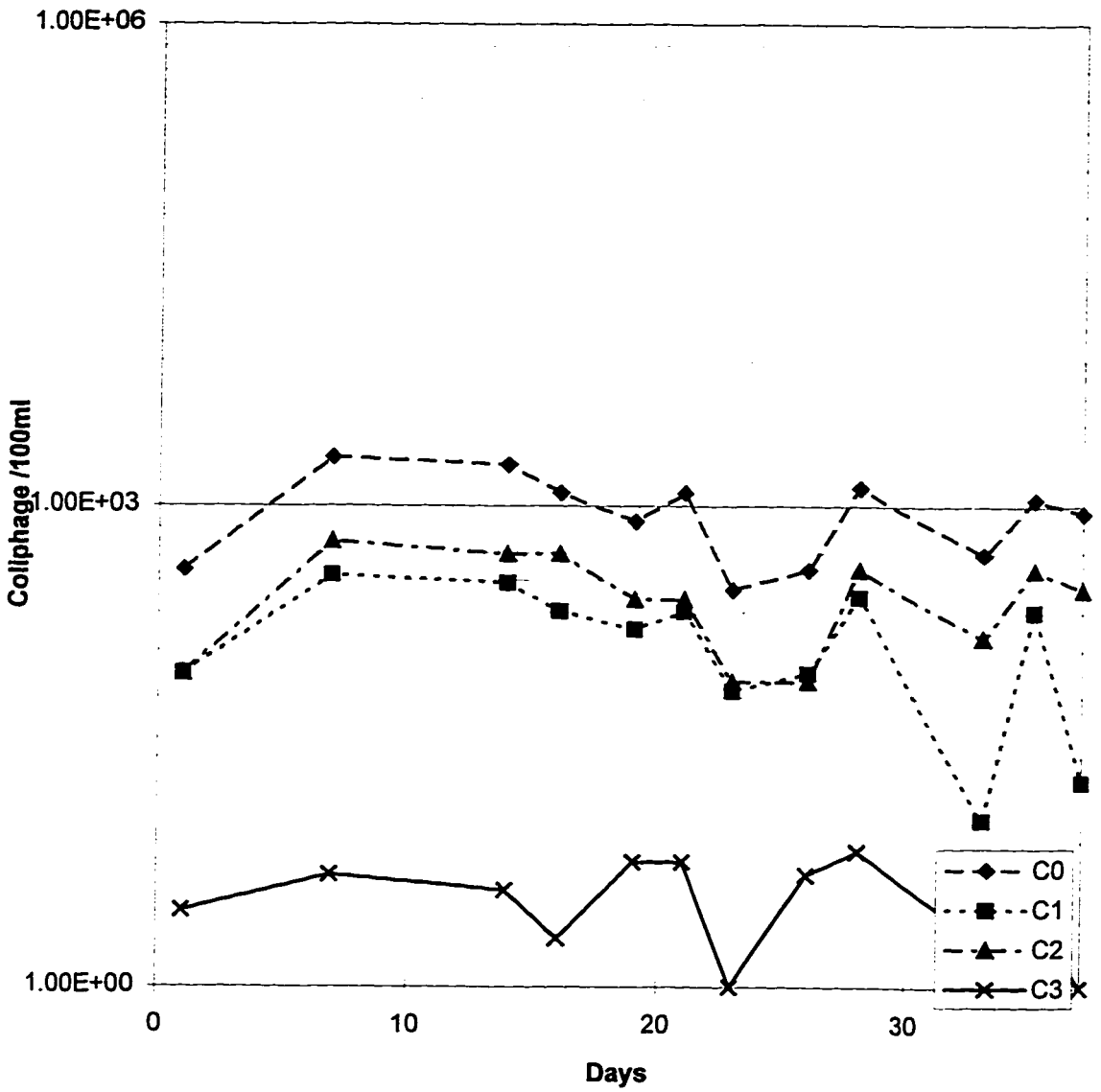


Fig 5.23 : Variation of Coliphage During Phase II

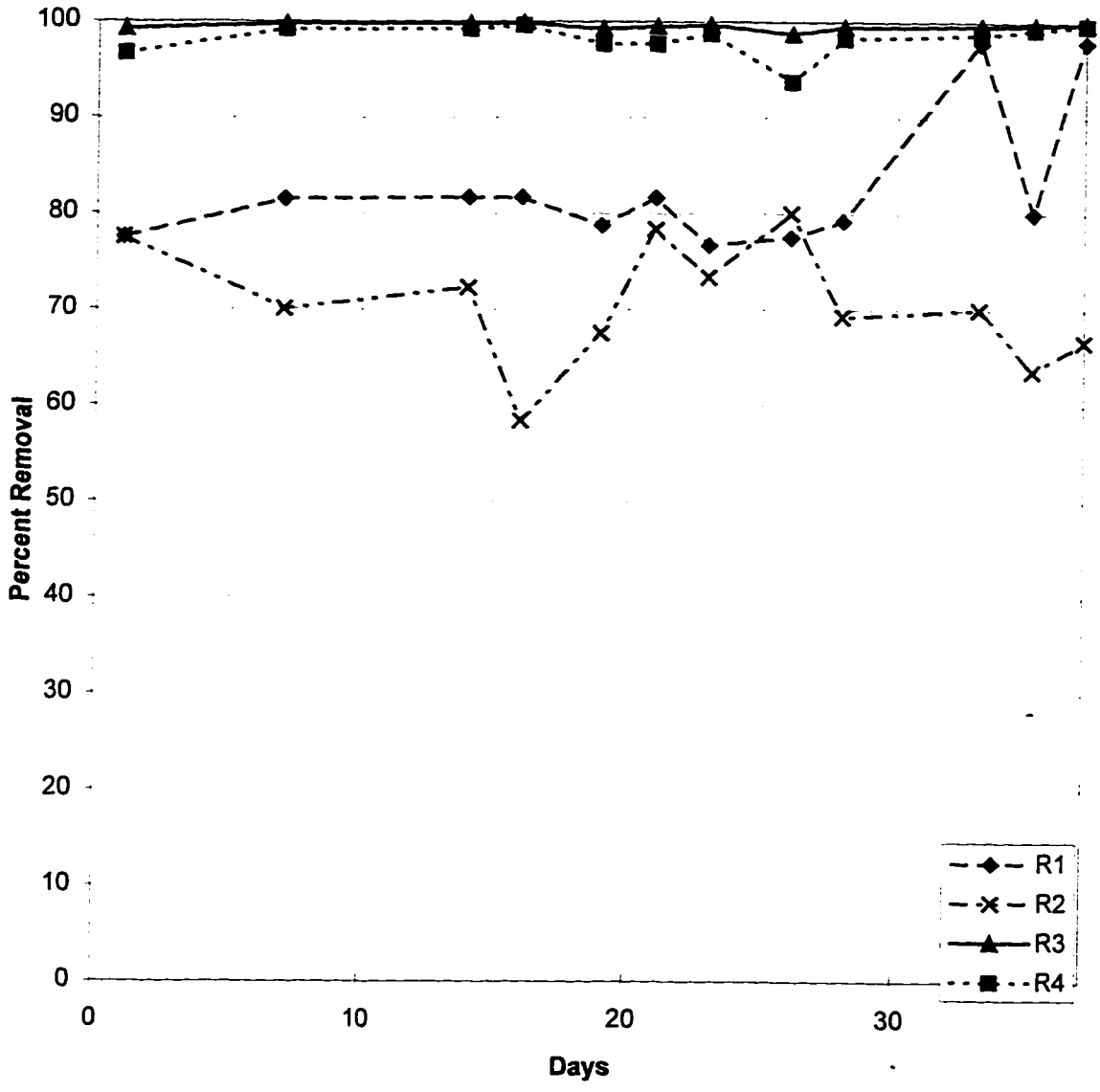


Fig 5.24 : Removals of Coliphage During Phase II

virus ratio of 10000:1, it can be safely assumed that most of the enteric viruses have been inactivated during slow sand filtration. Therefore the risk of enteric viruses in the filter effluents is very small.

This however may change due to the unforeseen changes in the health of the community. Here chlorination can act as an additional safety barrier. Relatively high numbers of the coliphage were recovered in both the chlorinated secondary effluents and the control filter effluent in both the phases compared to the test filter effluent. This shows that either chlorination or filtration alone is inadequate in the removal of viruses from the secondary effluent.

5.4 Effect of Pre-Chlorination Dose on the Removal of Indicator Organisms in Slow Sand Filtration

5.4.1 Modified Synergistic Model for Use with Slow Sand Filtration

The level of microbial inactivation in the treated wastewater is obtained by combining the Log Normal distribution model with the modified Berenbaums equation.

5.4.1.1 Step 1: Lognormal Distribution

The Lognormal distribution model is used when large uncertainty is present in the data. In this distribution variance is large function of the mean value. The microbial removals under different treatment levels were fitted on the Lognormal distribution and their cumulative probability distribution function (CDF) was found using mean rank formula. Although there was quite a large variation in influent values, it is assumed that conditions are steady in the influent and the concentration of the microbial indicator organisms is not a function of time.

The Log Normal probability density function (PDF) is given by

$$f(y_i) = \frac{1}{\sqrt{2\pi}sy_i}\left\{\frac{-1}{2s^2}\left(\ln y_i - \ln y_o\right)^2\right\} \qquad (5.1)$$

The cumulative distribution function (CDF) of the Log normal distribution is given by

$$F(y_i) = P(R_P \le y_i) = \Phi\left[\frac{1}{s}\ln\left(\frac{y}{y_o}\right)\right] \qquad (5.2)$$

Where

P = probability of desired safe levels

R_P = Desired safe level

y_i = variable ln[C/Co]

s = measure of scatter

To plot the curve of data, linearization of Eq.(5.2) is needed. In the linearized form Eq.5.2 becomes.

$$s\Phi^{-1}(F) = \ln(y_i) - \ln(y_o) \qquad (5.3)$$

therefore

$$\ln(y_i) = \ln(y_o) + s\Phi^{-1}(F) \qquad (5.4)$$

If the Eq.(5.4) is compared with Equation of straight line, following relations can be developed

$$Intercept = \ln y_o$$

$$Slope = s$$

Where y_o is the median value of the distribution and s the standard deviation of $\ln(y_i)$ and is a measure of scatter.

To plot the data of y for the various microorganisms, the natural log of the y_i values are taken on the Y-axis while the corresponding probabilities as estimated by the mean rank formula are taken on X-axis. The non parameteric estimate by mean rank formula

$$F(y_i) = P = \frac{i}{N+1} \qquad (5.5)$$

Where "N" is the total numbers of data points in each run.

The Lognormal distribution module option available in Microsoft Excel 7.0 was utilized to obtain the $\Phi^{-1}(F)$ for different values of F. Cumulative Probability Distribution Functions (CDF) for the C/Co for different treatments was found by linear regression with the ln[C/Co] values on the Y-axis and the corresponding $\Phi^{-1}(F)$ on the X-axis.

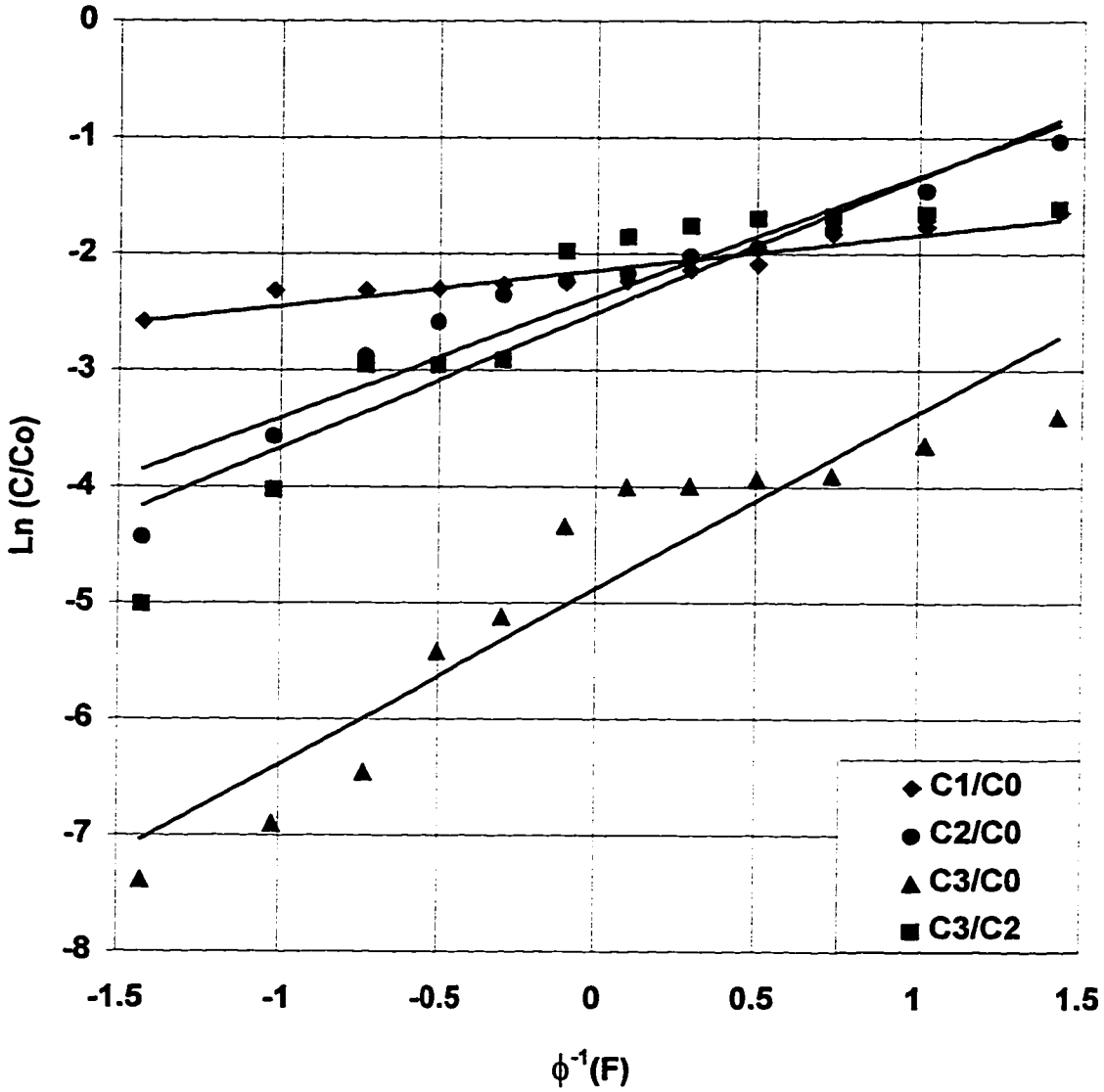
Table 5.13 gives a typical spreadsheet calculation for the Lognormal distribution. The C/Co values for all the treatment combinations are found out. Therefore COL#4 gives the C1/C0 values for the standard plate counts, which represent the removals in the control slow sand filter. Similarly COL#5, 6, and 7 give the C2/C0, C3/C0 and the C3/C2 values respectively. The natural logarithm of these values are given in the COL#8, 9, 10 and 11 respectively. COL#1 gives the rank of the removal values and the probability is given by F (COL#2). The transformation for F (COL#3) i.e., $\phi^{-1}(F)$ is obtained by using the EXCEL function NORMSINV. The values under COL#3 are plotted against those in COL#8, 9, 10 and 11. The Fig. 5.25 gives a typical regression chart for the determination of the cumulative probability distribution functions for standard plate counts. In Figure 5.25, the values in COL#3 are plotted against the values in COL#8, 9, 10 and 11. The EXCEL trend-line utility is utilized to obtain a best linear fit and its equation and R^2 values. A generic term of C/Co has been used throughout the analysis, where C represents the concentration of the microorganism after the treatment and Co represents the concentration of the microorganism before the treatment. Therefore the ratio C3/C0

Table 5.13: Calculations For Lognormal Distribution Fit (Standard Plate Count: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.07556	0.01190	0.00062	0.00667	-2.58289	-4.43082	-7.38733	-5.01064
2	0.15385	-1.02008	0.09870	0.02824	0.00100	0.01786	-2.31566	-3.56718	-6.90776	-4.02535
3	0.23077	-0.73632	0.09870	0.05600	0.00156	0.05200	-2.31566	-2.88240	-6.46407	-2.95651
4	0.30769	-0.50240	0.10000	0.07532	0.00441	0.05208	-2.30259	-2.58595	-5.42348	-2.95491
5	0.38462	-0.29338	0.10390	0.09532	0.00595	0.05429	-2.26436	-2.35047	-5.12396	-2.91349
6	0.46154	-0.09656	0.10588	0.10724	0.01299	0.13846	-2.24543	-2.23270	-4.34381	-1.97716
7	0.53846	0.09656	0.10714	0.11429	0.01818	0.15625	-2.23359	-2.16905	-4.00733	-1.85630
8	0.61538	0.29338	0.11796	0.13265	0.01837	0.17241	-2.13742	-2.02002	-3.99718	-1.75786
9	0.69231	0.50240	0.12381	0.14252	0.01939	0.18333	-2.08901	-1.94829	-3.94311	-1.69645
10	0.76923	0.73632	0.16086	0.16667	0.02011	0.18750	-1.82723	-1.79176	-3.90668	-1.67398
11	0.84615	1.02008	0.17102	0.23377	0.02613	0.19074	-1.76597	-1.45343	-3.64474	-1.65687
12	0.92308	1.42608	0.19524	0.35714	0.03333	0.20000	-1.63354	-1.02962	-3.40120	-1.60944

Table 5.14: Calculations For Lognormal Distribution Fit (Standard Plate Count: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.06080	0.00029	0.00008	0.09375	-2.80017	-8.14613	-9.43348	-2.36712
2	0.15385	-1.02008	0.06827	0.00042	0.00009	0.10714	-2.68432	-7.78483	-9.36449	-2.23359
3	0.23077	-0.73632	0.06857	0.00071	0.00009	0.11429	-2.67988	-7.24423	-9.35010	-2.16905
4	0.30769	-0.50240	0.07246	0.00072	0.00009	0.12000	-2.62467	-7.23569	-9.32367	-2.12026
5	0.38462	-0.29338	0.07381	0.00091	0.00010	0.12500	-2.60627	-6.99737	-9.18160	-2.07944
6	0.46154	-0.09656	0.08696	0.00109	0.00016	0.12500	-2.44235	-6.82437	-8.72149	-2.07944
7	0.53846	0.09656	0.09286	0.00292	0.00041	0.13333	-2.37669	-5.83731	-7.80384	-2.01490
8	0.61538	0.29338	0.10972	0.00357	0.00048	0.14286	-2.20980	-5.63479	-7.64969	-1.94591
9	0.69231	0.50240	0.11837	0.00381	0.00051	0.15000	-2.13396	-5.57025	-7.58070	-1.89712
10	0.76923	0.73632	0.12245	0.00408	0.00071	0.19231	-2.10006	-5.50126	-7.24423	-1.64866
11	0.84615	1.02008	0.13333	0.00595	0.00082	0.28571	-2.01490	-5.12396	-7.11070	-1.25276
12	0.92308	1.42608	0.19286	0.00714	0.00083	0.30000	-1.64581	-4.94164	-7.09008	-1.20397



◆ $y = 0.3052x - 2.1428$
$R^2 = 0.9047$

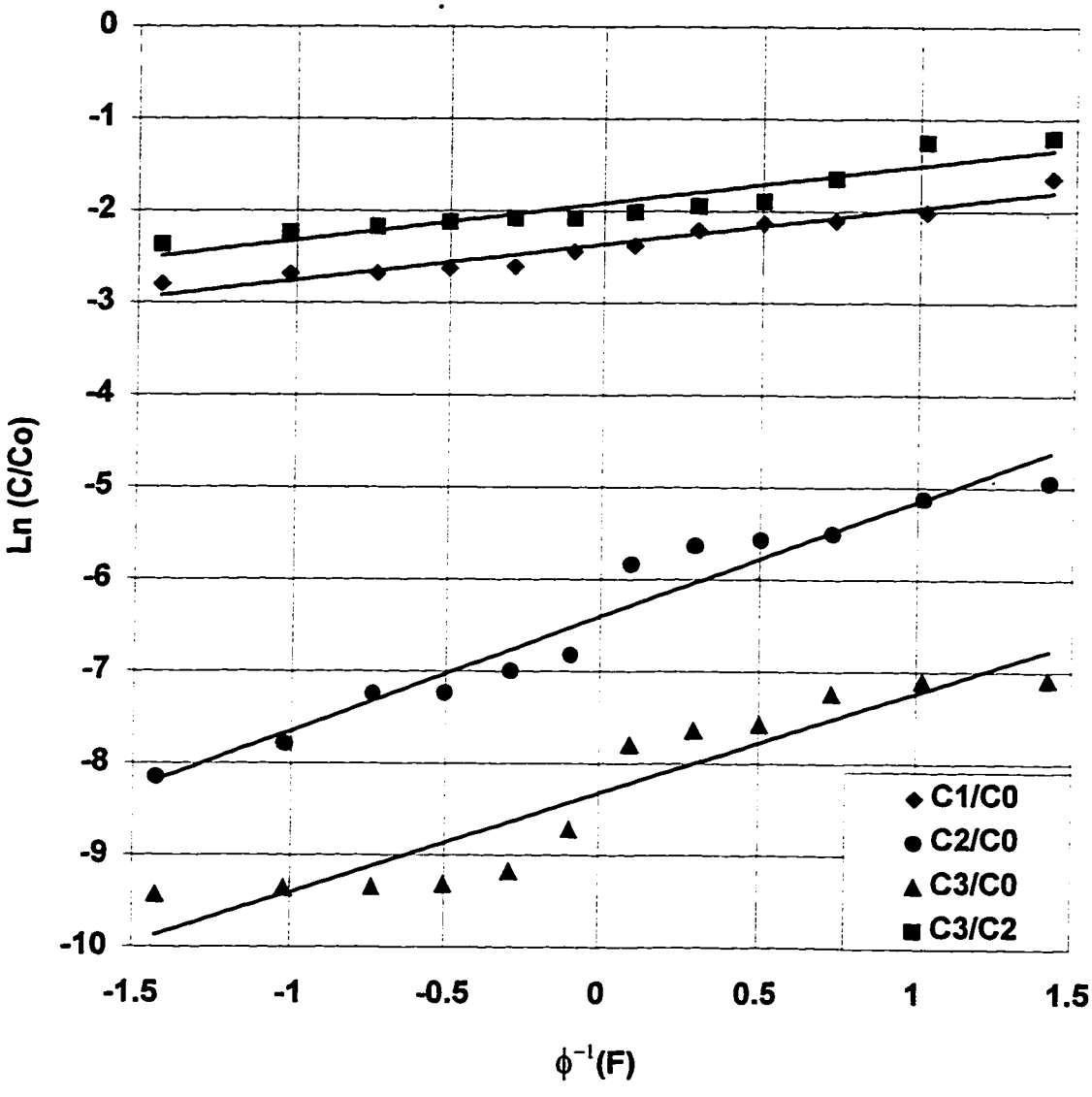
▲ $y = 1.5139x - 4.8792$
$R^2 = 0.8809$

■ $y = 1.1596x - 2.5074$
$R^2 = 0.8024$

● $y = 1.0384x - 2.3718$
$R^2 = 0.9173$

Figure 5.25 : Lognormal Distribution Fit for Standard Plate Count Removal During Phase I

represents the concentration ratio in the test filter, utilizing the chlorinated secondary effluents. C1/C0 gives the concentration ratio for the removals in the control filter, and C2/C0 gives the removal due to chlorination of the secondary effluents alone. It should be noted that the concentration ratios can be converted to percent removal and vice versa. Figures 5.25 and 5.26 give the regression plots of the ranked ln[C/Co] values for standard plate count indicators during Phase I and II. The CDFs and their respective R^2 values are given on the same figures. The corresponding fits for total coliform, fecal coliform, fecal streptococcus, *Clostridium perfringens* and coliphages are given in Figs. 5.27 and 5.28, Figs. 5.29 and 5.30, Figs. 5.31 and 5.32, Figs. 5.33 and 5.34, and Figs 5.35 and 5.36 respectively for both the phases. The $P(R_P \leq x)$ values for a range of different Rp levels of the indicator organisms can be obtained by solving the CDF obtained in the Lognormal distribution. This gives the probability that the safe levels x, will be less than or equal to the desired safe level R_P. A typical spreadsheet solution for the xi values can be seen in Table 5.25 in which the CDF's (Shaded Row) are solved over a range of Rp values (COL#1). Therefore COL#3, 4, 5, and 6 represent the probability of achieving an Rp level of removal under different treatment schemes. A typical probability plot for the probability of meeting the desired safe levels Rp for the different indicator organisms in phase I is given in Fig 5.37. This has been obtained by plotting the values in COL#1 on the y axis against the values of COL#3, 4, 5 and 6 on the x axis. The corresponding



◆ y = 0.3942x - 2.3599
R^2 = 0.9408

■ y = 0.4036x - 1.9177
R^2 = 0.8651

▲ y = 1.0854x - 8.3212
R^2 = 0.8731

● y = 1.2486x - 6.4035
R^2 = 0.9458

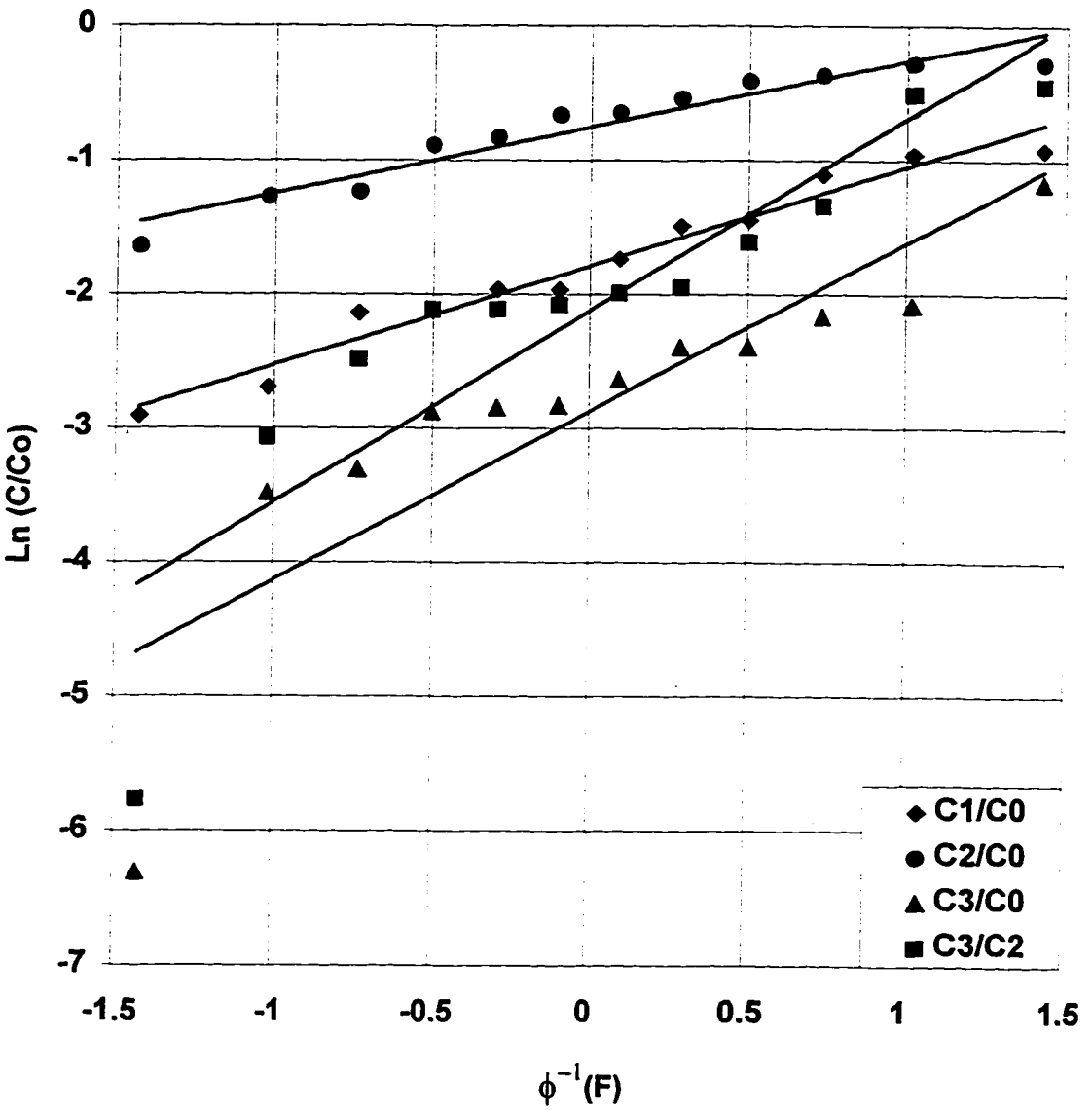
Figure 5.26 : Lognormal Distribution Fit for Standard Plate Count Removal During Phase II

Table 5.15: Calculations For Lognormal Distribution Fit (Total Coliform: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.07361	0.10377	0.00333	0.02556	-2.60896	-2.26554	-5.70378	-3.66690
2	0.15385	-1.02008	0.08491	0.12917	0.00383	0.02581	-2.46621	-2.04665	-5.56402	-3.65713
3	0.23077	-0.73632	0.11833	0.15000	0.00453	0.04250	-2.13425	-1.89712	-5.39741	-3.15825
4	0.30769	-0.50240	0.13462	0.22222	0.01259	0.04364	-2.00533	-1.50408	-4.37465	-3.13186
5	0.38462	-0.29338	0.15294	0.23939	0.01364	0.05696	-1.87770	-1.42964	-4.29502	-2.86537
6	0.46154	-0.09656	0.15758	0.24390	0.01750	0.06125	-1.84785	-1.41099	-4.04555	-2.79279
7	0.53846	0.09656	0.17037	0.25000	0.01857	0.06500	-1.76978	-1.38629	-3.98613	-2.73337
8	0.61538	0.29338	0.17857	0.28571	0.02000	0.08923	-1.72277	-1.25276	-3.91202	-2.41653
9	0.69231	0.50240	0.17857	0.28571	0.02231	0.09000	-1.72277	-1.25276	-3.80282	-2.40795
10	0.76923	0.73632	0.17857	0.28571	0.02439	0.10000	-1.72277	-1.25276	-3.71357	-2.30259
11	0.84615	1.02008	0.20000	0.29630	0.03500	0.12250	-1.60944	-1.21640	-3.35241	-2.09964
12	0.92308	1.42608	0.36585	0.31765	0.04118	0.12963	-1.00552	-1.14681	-3.18989	-2.04307

Table 5.16: Calculations For Lognormal Distribution Fit (Total Coliform: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.08857	0.00024	0.00001	0.03333	-2.42395	-8.35467	-11.15625	-3.40120
2	0.15385	-1.02008	0.15385	0.00031	0.00003	0.03636	-1.87180	-8.08641	-10.46310	-3.31419
3	0.23077	-0.73632	0.17778	0.00036	0.00003	0.04000	-1.72722	-7.93737	-10.46310	-3.21888
4	0.30769	-0.50240	0.17778	0.00043	0.00003	0.04444	-1.72722	-7.75505	-10.46310	-3.11352
5	0.38462	-0.29338	0.18333	0.00044	0.00004	0.05455	-1.69645	-7.71869	-10.22194	-2.90872
6	0.46154	-0.09656	0.18571	0.00065	0.00004	0.06667	-1.68355	-7.34307	-10.02127	-2.70805
7	0.53846	0.09656	0.19286	0.00079	0.00005	0.07273	-1.64581	-7.14892	-9.96411	-2.62104
8	0.61538	0.29338	0.19412	0.00082	0.00005	0.09167	-1.63929	-7.10843	-9.82938	-2.38960
9	0.69231	0.50240	0.19412	0.00086	0.00007	0.10000	-1.63929	-7.06191	-9.61581	-2.30259
10	0.76923	0.73632	0.20000	0.00100	0.00007	0.17500	-1.60944	-6.90776	-9.55865	-1.74297
11	0.84615	1.02008	0.22222	0.00122	0.00012	0.21667	-1.50408	-6.70708	-9.00967	-1.52940
12	0.92308	1.42608	0.22857	0.00133	0.00022	0.30000	-1.47591	-6.62007	-8.43715	-1.20397



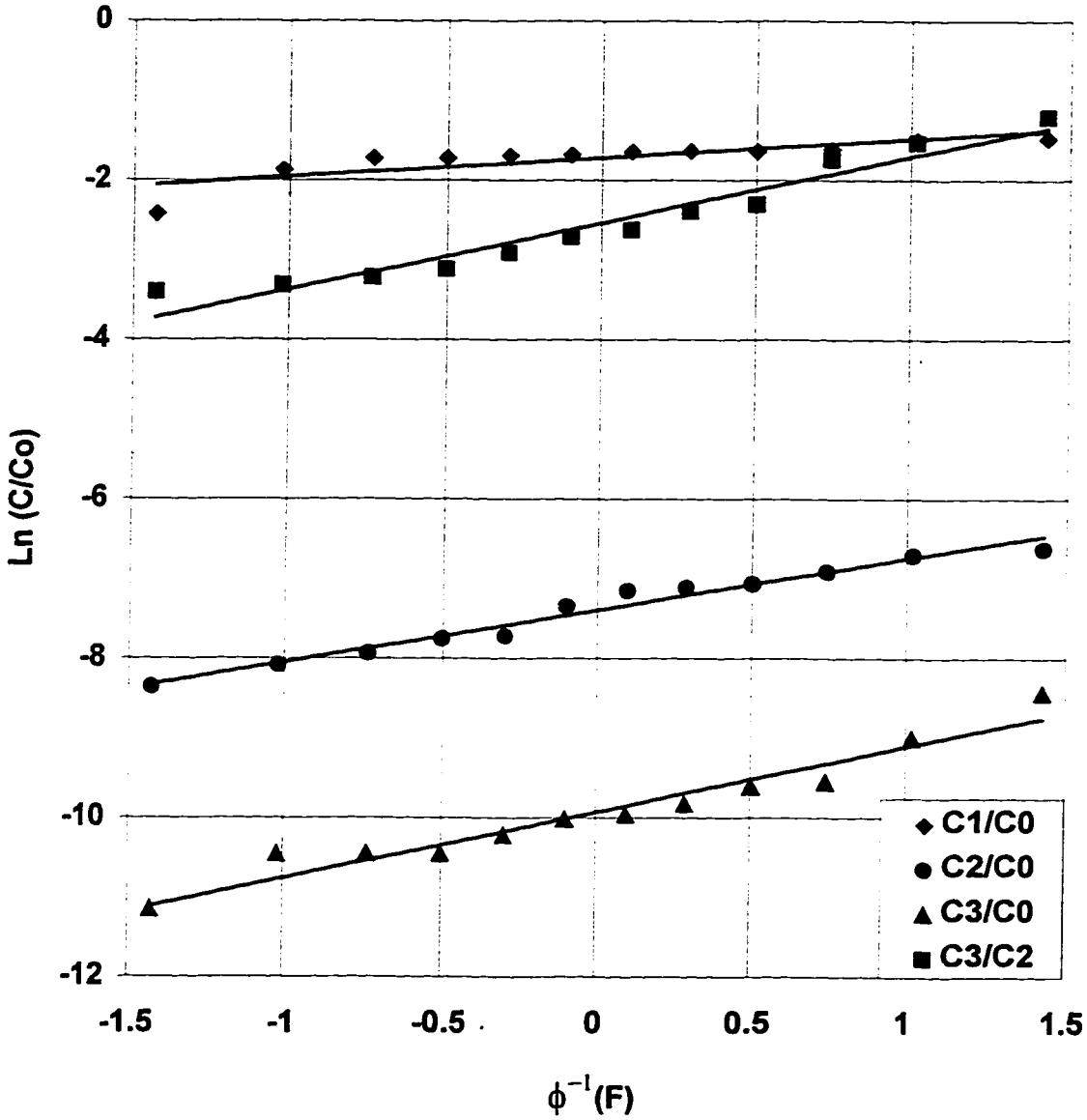
◆ y = 0.7398x - 1.788
R^2 = 0.9671

▲ y = 1.2594x - 2.8778
R^2 = 0.7447

■ y = 1.432x - 2.1234
R^2 = 0.7874

● y = 0.4928x - 0.7544
R^2 = 0.926

Figure 5.27 : Lognormal Distribution Fit for Total Coliform Removal During Phase I



◆ $y = 0.2369x - 1.7203$
$R^2 = 0.6768$

▲ $y = 0.829x - 9.9336$
$R^2 = 0.9438$

■ $y = 0.8336x - 2.5378$
$R^2 = 0.9462$

● $y = 0.654x - 7.3958$
$R^2 = 0.9701$

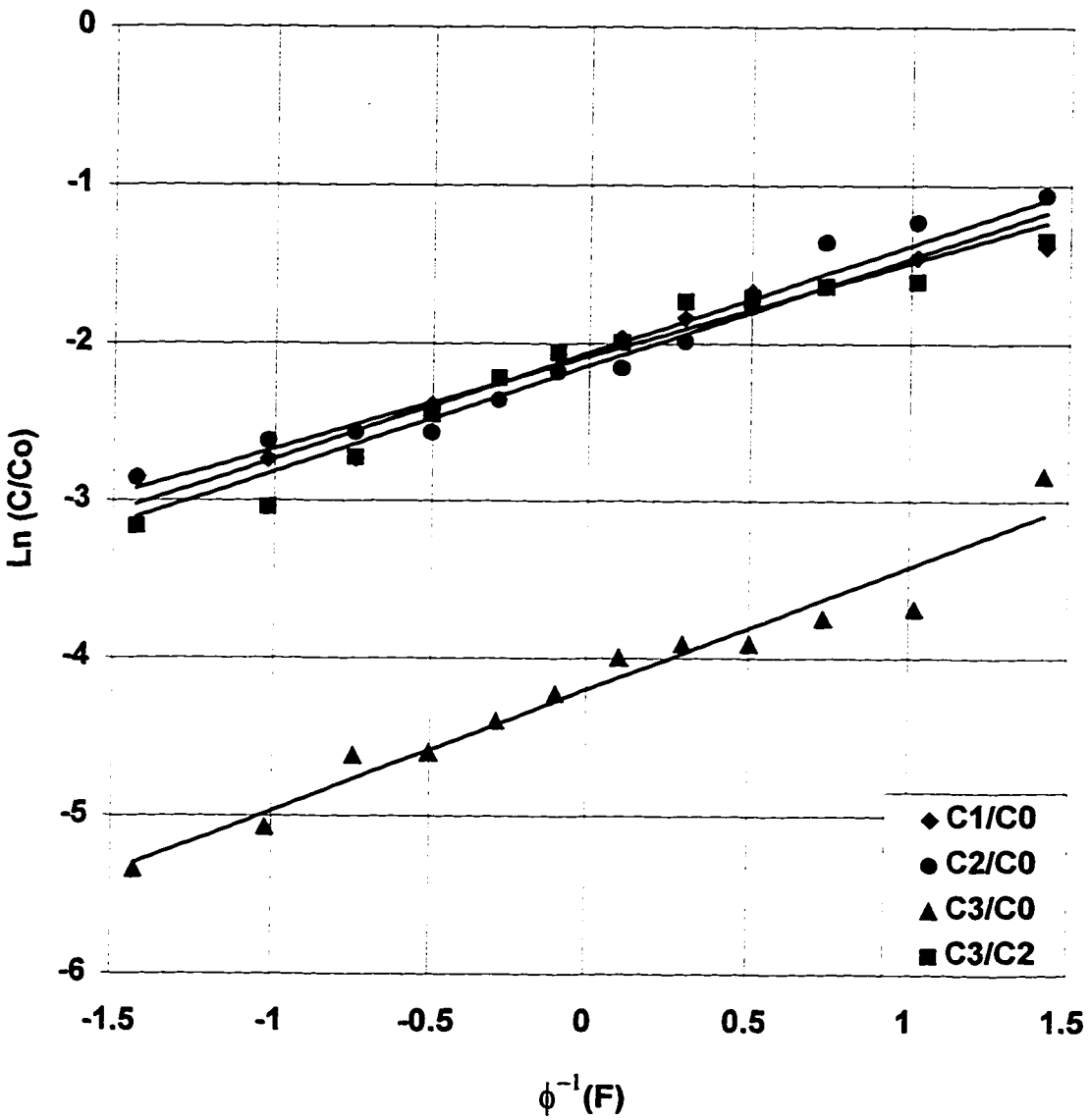
Figure 5.28 : Lognormal Distribution Fit for Total Coliform Removal During Phase II

Table 5.17: Calculations For Lognormal Distribution Fit (Fecal Coliform: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.05769	0.05750	0.00477	0.04222	-2.85263	-2.85597	-5.34484	-3.16481
2	0.15385	-1.02008	0.06462	0.07273	0.00625	0.04778	-2.73930	-2.62104	-5.07517	-3.04119
3	0.23077	-0.73632	0.06500	0.07692	0.00985	0.06563	-2.73337	-2.56495	-4.62067	-2.72380
4	0.30769	-0.50240	0.09143	0.07692	0.01000	0.08621	-2.39220	-2.56495	-4.60517	-2.45101
5	0.38462	-0.29338	0.10833	0.09444	0.01229	0.10870	-2.22254	-2.35974	-4.39932	-2.21920
6	0.46154	-0.09656	0.12615	0.11333	0.01462	0.12800	-2.07025	-2.17742	-4.22568	-2.05573
7	0.53846	0.09656	0.14000	0.11600	0.01833	0.13636	-1.96611	-2.15417	-3.99903	-1.99243
8	0.61538	0.29338	0.15909	0.13750	0.02000	0.17647	-1.83828	-1.98413	-3.91202	-1.73460
9	0.69231	0.50240	0.18750	0.17188	0.02000	0.18182	-1.67398	-1.76099	-3.91202	-1.70475
10	0.76923	0.73632	0.19444	0.25714	0.02344	0.19412	-1.63761	-1.35812	-3.75342	-1.63929
11	0.84615	1.02008	0.23333	0.29167	0.02500	0.20000	-1.45529	-1.23214	-3.68888	-1.60944
12	0.92308	1.42608	0.25000	0.34615	0.05833	0.26000	-1.38629	-1.06087	-2.84158	-1.34707

Table 5.18: Calculations For Lognormal Distribution Fit (Fecal Coliform: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.02889	0.00012	0.00002	0.02500	-3.54430	-9.00270	-11.08214	-3.68888
2	0.15385	-1.02008	0.15455	0.00016	0.00002	0.04000	-1.86727	-8.75836	-10.91509	-3.21888
3	0.23077	-0.73632	0.16923	0.00022	0.00002	0.05000	-1.77649	-8.44309	-10.81978	-2.99573
4	0.30769	-0.50240	0.17143	0.00025	0.00002	0.05714	-1.76359	-8.27603	-10.71442	-2.86220
5	0.38462	-0.29338	0.17143	0.00032	0.00003	0.05714	-1.76359	-8.05289	-10.59663	-2.86220
6	0.46154	-0.09656	0.18000	0.00037	0.00003	0.09091	-1.71480	-7.91106	-10.38900	-2.39790
7	0.53846	0.09656	0.18750	0.00044	0.00003	0.12500	-1.67398	-7.71869	-10.30895	-2.07944
8	0.61538	0.29338	0.19091	0.00063	0.00004	0.14000	-1.65596	-7.37776	-10.22194	-1.96611
9	0.69231	0.50240	0.19286	0.00071	0.00005	0.14286	-1.64581	-7.24423	-9.90349	-1.94591
10	0.76923	0.73632	0.25385	0.00080	0.00006	0.14286	-1.37103	-7.13090	-9.76996	-1.94591
11	0.84615	1.02008	0.26667	0.00086	0.00010	0.20000	-1.32176	-7.06191	-9.21034	-1.60944
12	0.92308	1.42608	0.28571	0.00100	0.00017	0.31818	-1.25276	-6.90776	-8.67134	-1.14513



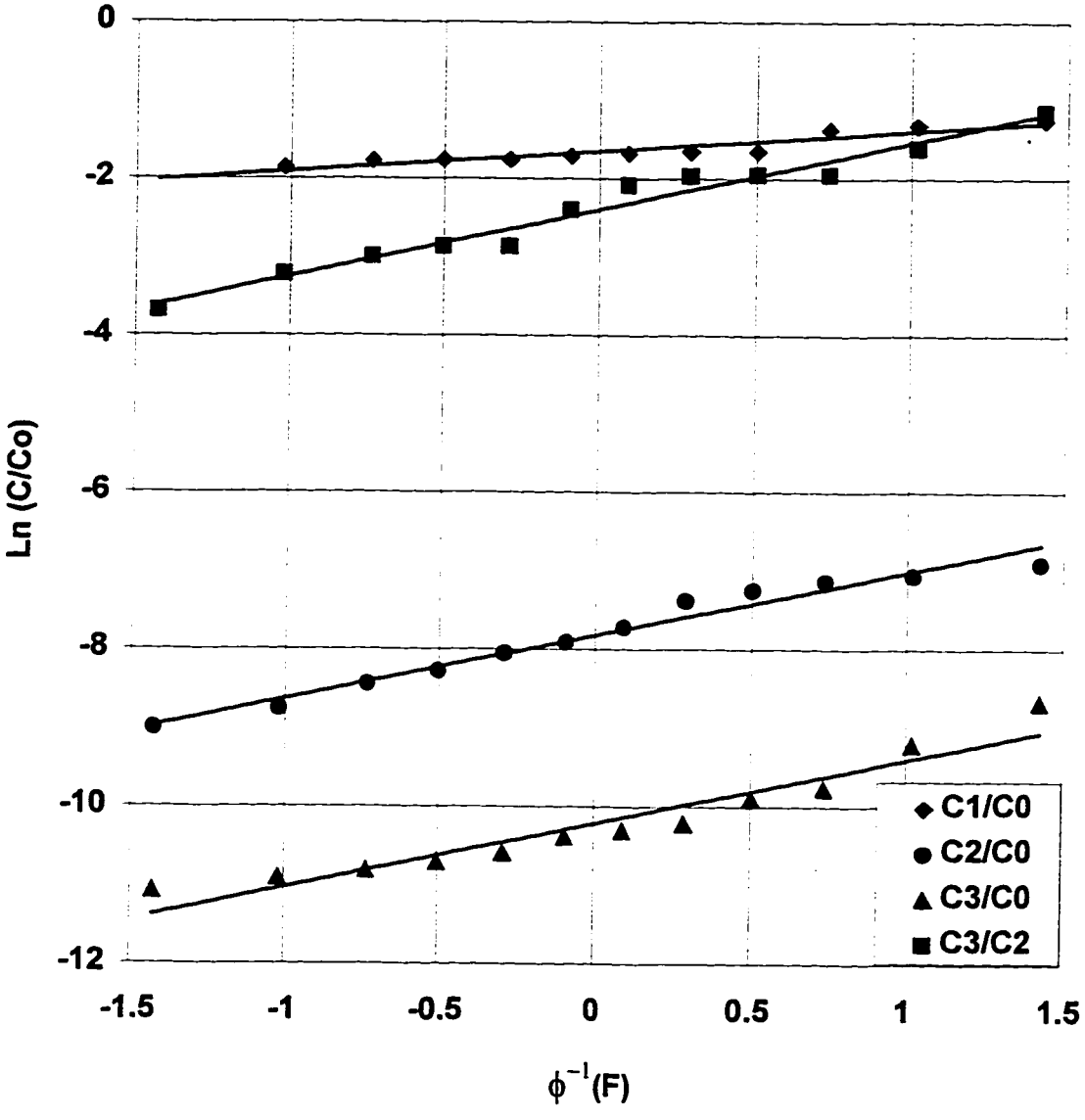
◆ $y = 0.5917x - 2.0807$
$R^2 = 0.9639$

▲ $y = 0.7739x - 4.1982$
$R^2 = 0.9553$

■ $y = 0.6779x - 2.1403$
$R^2 = 0.9463$

● $y = 0.6788x - 2.0579$
$R^2 = 0.9508$

Figure 5.29 : Lognormal Distribution Fit for Fecal Coliform Removal During Phase I



◆ $y = 0.2578x - 1.6522$
$R^2 = 0.8894$

▲ $y = 0.8167x - 10.217$
$R^2 = 0.923$

■ $y = 0.8572x - 2.3931$
$R^2 = 0.9683$

● $y = 0.8097x - 7.8238$
$R^2 = 0.9702$

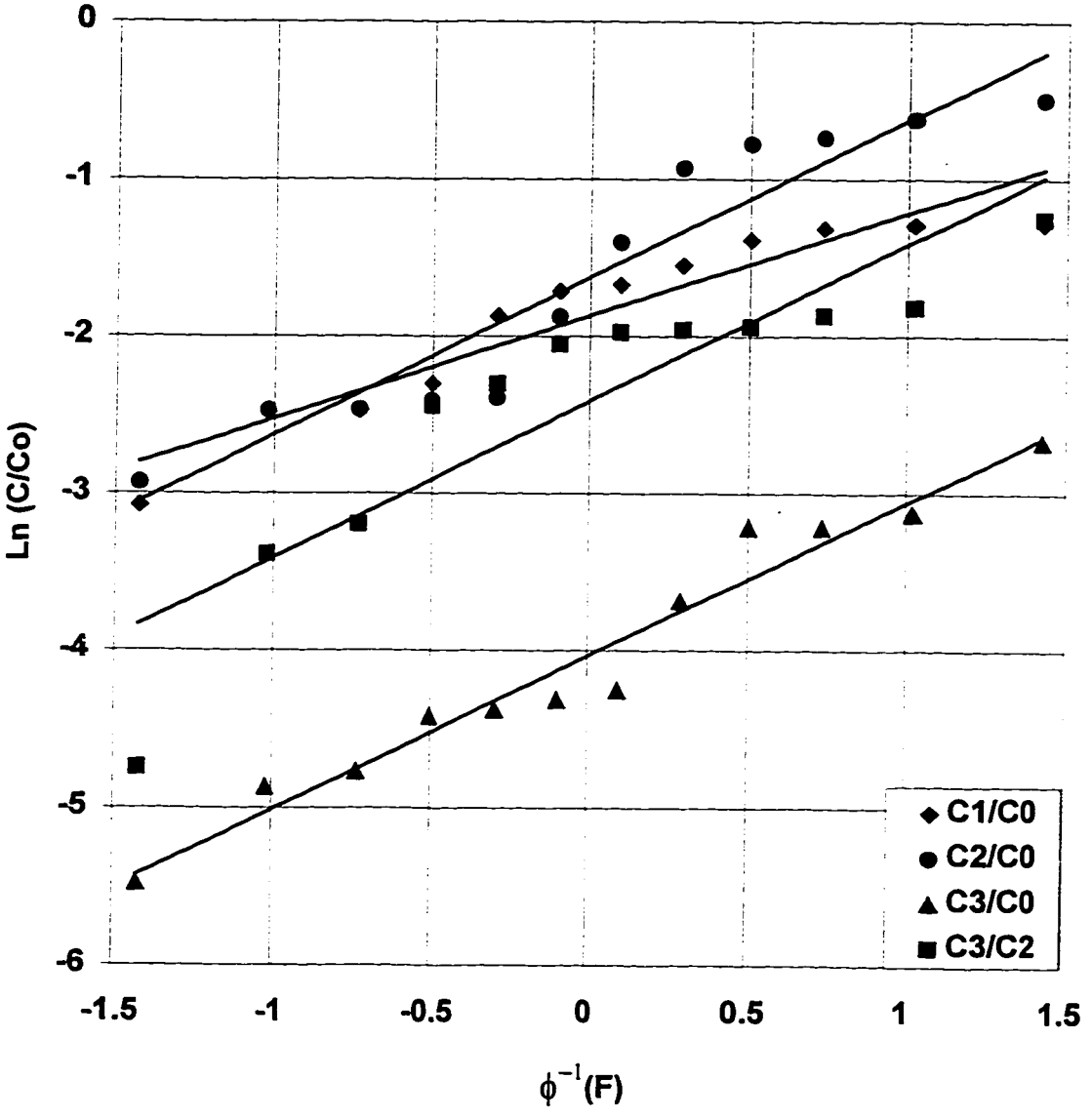
Figure 5.30 : Lognormal Distribution Fit for Fecal Coliform Removal During Phase II

Table 5.19: Calculations For Lognormal Distribution Fit (Fecal Streptococcus: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.04611	0.05333	0.00417	0.00870	-3.07670	-2.93119	-5.48064	-4.74493
2	0.15385	-1.02008	0.08333	0.08462	0.00767	0.03380	-2.48491	-2.46964	-4.87087	-3.38721
3	0.23077	-0.73632	0.08462	0.08500	0.00846	0.04091	-2.46964	-2.46510	-4.77222	-3.19640
4	0.30769	-0.50240	0.10000	0.09000	0.01200	0.08696	-2.30259	-2.40795	-4.42285	-2.44235
5	0.38462	-0.29338	0.15385	0.09167	0.01250	0.10000	-1.87180	-2.38960	-4.38203	-2.30259
6	0.46154	-0.09656	0.18000	0.15313	0.01333	0.12857	-1.71480	-1.87650	-4.31749	-2.05127
7	0.53846	0.09656	0.18750	0.24615	0.01417	0.13889	-1.67398	-1.40180	-4.25686	-1.97408
8	0.61538	0.29338	0.21250	0.39444	0.02500	0.14118	-1.54881	-0.93028	-3.68888	-1.95774
9	0.69231	0.50240	0.25000	0.46000	0.04000	0.14375	-1.38629	-0.77653	-3.21888	-1.93968
10	0.76923	0.73632	0.26923	0.47917	0.04000	0.15455	-1.31219	-0.73571	-3.21888	-1.86727
11	0.84615	1.02008	0.27500	0.53846	0.04375	0.16250	-1.29098	-0.61904	-3.12926	-1.81708
12	0.92308	1.42608	0.27778	0.61111	0.06923	0.28571	-1.28093	-0.49248	-2.67031	-1.25276

Table 5.20: Calculations For Lognormal Distribution Fit (Fecal Streptococcus: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.04375	0.00034	0.00003	0.09091	-3.12926	-7.97560	-10.37349	-2.39790
2	0.15385	-1.02008	0.07143	0.00078	0.00011	0.09091	-2.63906	-7.15907	-9.10498	-2.39790
3	0.23077	-0.73632	0.11111	0.00080	0.00014	0.11111	-2.19722	-7.13090	-8.85367	-2.19722
4	0.30769	-0.50240	0.12500	0.00114	0.00014	0.12500	-2.07944	-6.77422	-8.85367	-2.07944
5	0.38462	-0.29338	0.13333	0.00129	0.00025	0.14286	-2.01490	-6.65644	-8.29405	-1.94591
6	0.46154	-0.09656	0.14000	0.00157	0.00029	0.22222	-1.96611	-6.45577	-8.16052	-1.50408
7	0.53846	0.09656	0.14000	0.00175	0.00040	0.25000	-1.96611	-6.34814	-7.82405	-1.38629
8	0.61538	0.29338	0.14000	0.00200	0.00067	0.25000	-1.96611	-6.21461	-7.31322	-1.38629
9	0.69231	0.50240	0.15385	0.00220	0.00077	0.36364	-1.87180	-6.11930	-7.17012	-1.01160
10	0.76923	0.73632	0.15714	0.00220	0.00080	0.36364	-1.85060	-6.11930	-7.13090	-1.01160
11	0.84615	1.02008	0.15714	0.00300	0.00080	0.50000	-1.85060	-5.80914	-7.13090	-0.69315
12	0.92308	1.42608	0.17500	0.00308	0.00100	0.57143	-1.74297	-5.78383	-6.90776	-0.55962



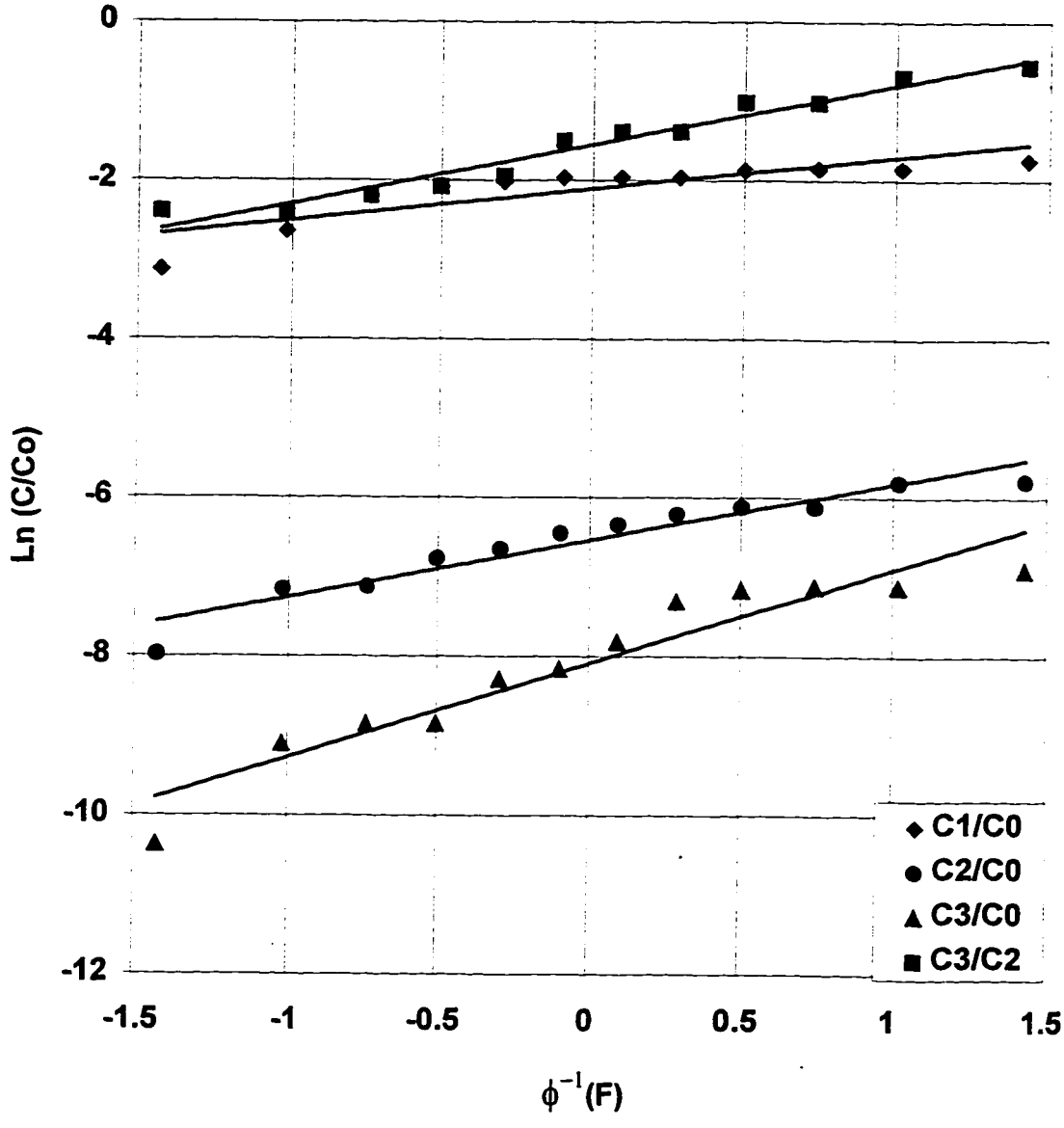
◆ y = 0.6546x - 1.8678
R^2 = 0.9003

▲ y = 0.9765x - 4.0358
R^2 = 0.9611

■ y = 0.9991x - 2.4111
R^2 = 0.8103

● y = 1.0005x - 1.6247
R^2 = 0.9098

Figure 5.31 : Lognormal Distribution Fit for Fecal Streptococcus Removal During Phase I



◆ y = 0.3979x - 2.1062
R^2 = 0.7281

▲ y = 1.1844x - 8.0931
R^2 = 0.9106

■ y = 0.7499x - 1.5476
R^2 = 0.96

● y = 0.721x - 6.5455
R^2 = 0.9219

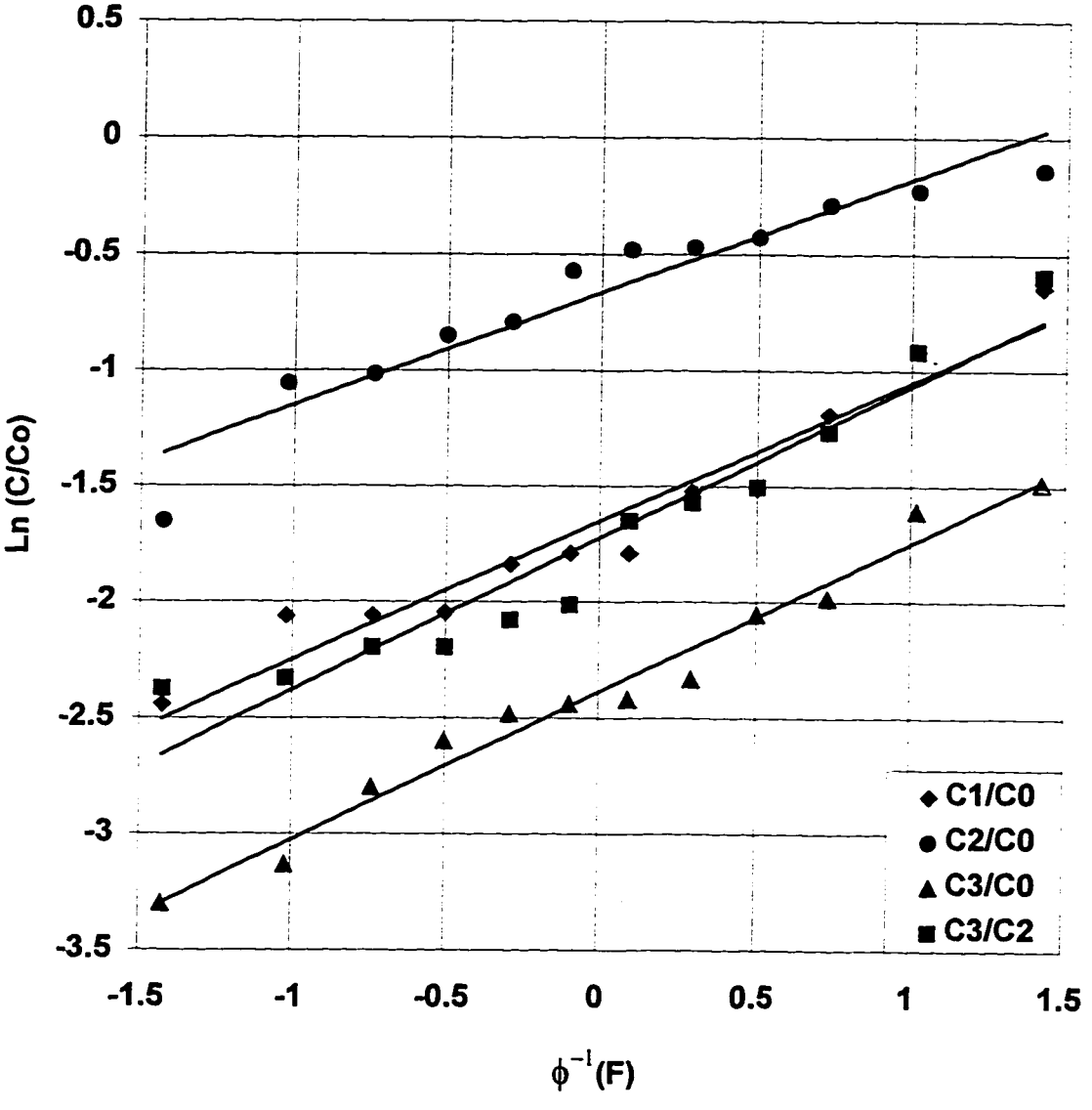
Figure 5.32 : Lognormal Distribution Fit for Fecal Streptococcus Removal During Phase II

Table 5.21: Calculations For Lognormal Distribution Fit (*Clostridium perfringens*: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.08696	0.19186	0.03682	0.09302	-2.44235	-1.65099	-3.30167	-2.37491
2	0.15385	-1.02008	0.12707	0.34783	0.04348	0.09735	-2.06300	-1.05605	-3.13549	-2.32949
3	0.23077	-0.73632	0.12745	0.36250	0.06077	0.11111	-2.06002	-1.01473	-2.80060	-2.19722
4	0.30769	-0.50240	0.12903	0.42742	0.07407	0.11111	-2.04769	-0.84999	-2.60269	-2.19722
5	0.38462	-0.29338	0.15891	0.45349	0.08333	0.12500	-1.83939	-0.79079	-2.48491	-2.07944
6	0.46154	-0.09656	0.16667	0.56391	0.08696	0.13333	-1.79176	-0.57286	-2.44235	-2.01490
7	0.53846	0.09656	0.16667	0.61765	0.08871	0.19192	-1.79176	-0.48184	-2.42239	-1.65068
8	0.61538	0.29338	0.21774	0.62431	0.09677	0.20755	-1.52444	-0.47111	-2.33537	-1.57240
9	0.69231	0.50240	0.22093	0.65217	0.12791	0.22222	-1.50991	-0.42744	-2.05645	-1.50408
10	0.76923	0.73632	0.30435	0.75000	0.13725	0.28205	-1.18958	-0.28768	-1.98592	-1.26567
11	0.84615	1.02008	0.40000	0.79630	0.20000	0.40000	-0.91629	-0.22778	-1.60944	-0.91629
12	0.92308	1.42608	0.52632	0.87097	0.22556	0.55172	-0.64185	-0.13815	-1.48915	-0.59471

Table 5.22: Calculations For Lognormal Distribution Fit (*Clostridium perfringens*: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.16667	0.03871	0.00667	0.01818	-1.79176	-3.25167	-5.01064	-4.00733
2	0.15385	-1.02008	0.16923	0.04500	0.00750	0.02000	-1.77649	-3.10109	-4.89285	-3.91202
3	0.23077	-0.73632	0.17500	0.04615	0.00769	0.02727	-1.74297	-3.07577	-4.86753	-3.60187
4	0.30769	-0.50240	0.18710	0.05000	0.00833	0.05000	-1.67613	-2.99573	-4.78749	-2.99573
5	0.38462	-0.29338	0.18750	0.07000	0.01250	0.06250	-1.67398	-2.65926	-4.38203	-2.77259
6	0.46154	-0.09656	0.18750	0.24000	0.01750	0.06667	-1.67398	-1.42712	-4.04555	-2.70805
7	0.53846	0.09656	0.20500	0.36667	0.01875	0.07292	-1.58475	-1.00330	-3.97656	-2.61844
8	0.61538	0.29338	0.20714	0.41667	0.01935	0.16667	-1.57435	-0.87547	-3.94481	-1.79176
9	0.69231	0.50240	0.20769	0.44444	0.02000	0.16667	-1.57170	-0.81093	-3.91202	-1.79176
10	0.76923	0.73632	0.22222	0.46154	0.02778	0.25000	-1.50408	-0.77319	-3.58352	-1.38629
11	0.84615	1.02008	0.22500	0.57143	0.02857	0.28571	-1.49165	-0.55962	-3.55535	-1.25276
12	0.92308	1.42608	0.25000	0.68750	0.03077	0.50000	-1.38629	-0.37469	-3.48124	-0.69315



◆ y = 0.598x - 1.6515
R^2 = 0.9441

▲ y = 0.6384x - 2.3889
R^2 = 0.9757

■ y = 0.6557x - 1.7248
R^2 = 0.9303

● y = 0.4859x - 0.6641
R^2 = 0.9156

Figure 5.33 : Lognormal Distribution Fit for *Clostridium perfringens* Removal During Phase I

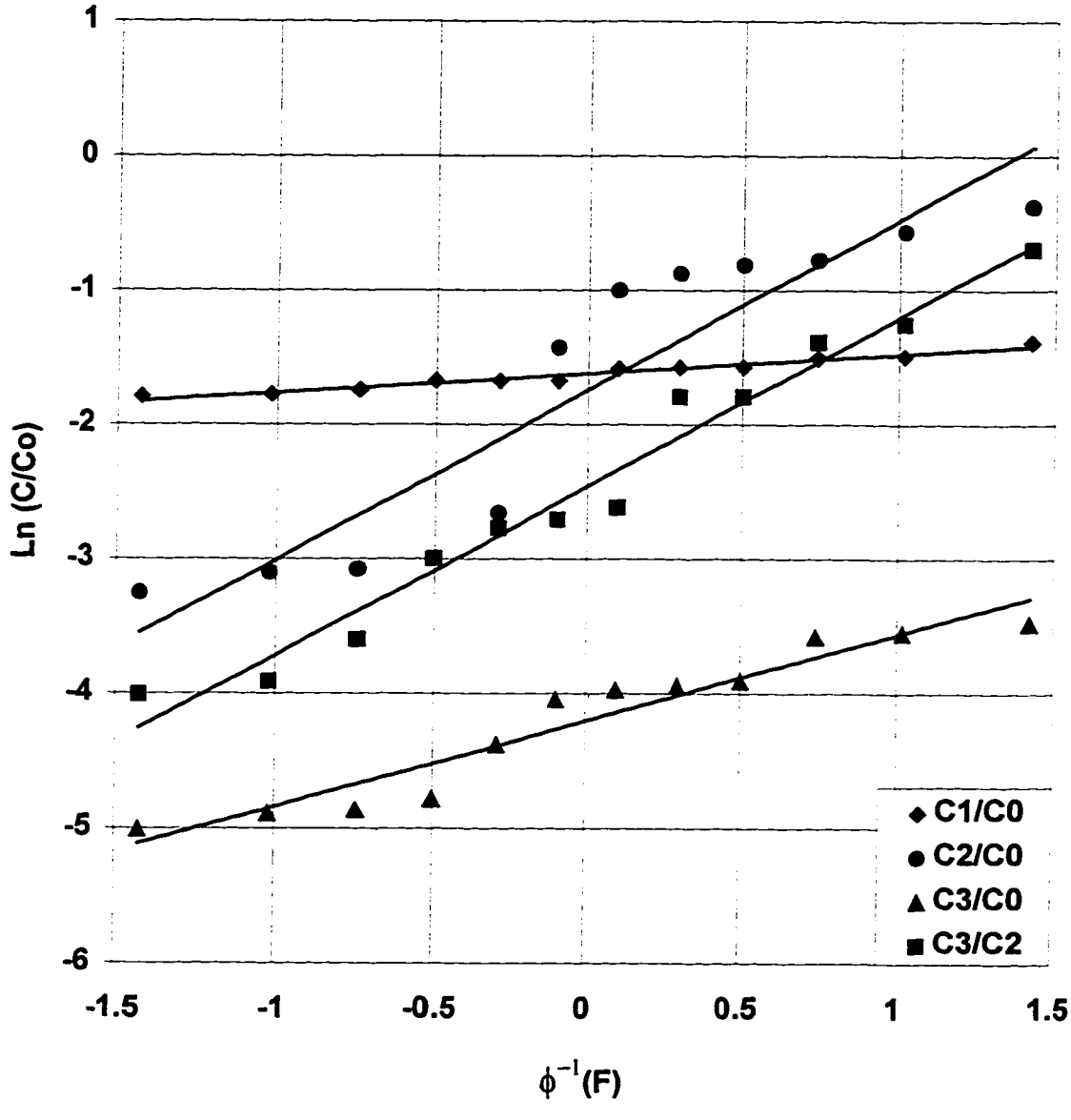


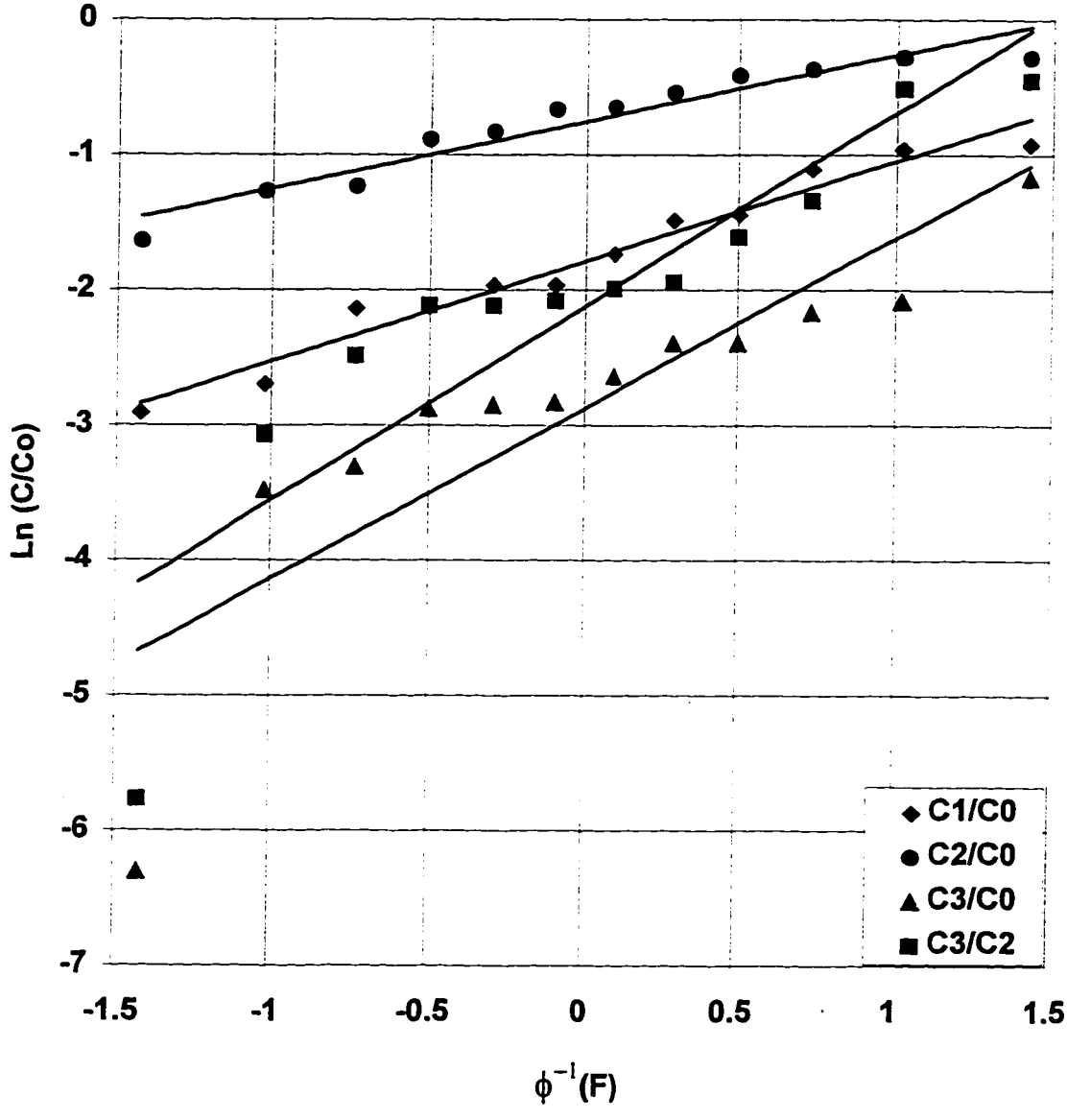
Figure 5.34 : Lognormal Distribution Fit for *Clostridium perfringens* Removal During Phase II

Table 5.23: Calculations For Lognormal Distribution Fit (Coliphage Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.05455	0.19421	0.00182	0.00313	-2.90872	-1.63879	-6.30992	-5.76832
2	0.15385	-1.02008	0.06742	0.28090	0.03065	0.04634	-2.69688	-1.26976	-3.48528	-3.07172
3	0.23077	-0.73632	0.11774	0.29167	0.03646	0.08333	-2.13926	-1.23214	-3.31159	-2.48491
4	0.30769	-0.50240	0.11979	0.41176	0.05618	0.12059	-2.12200	-0.88730	-2.87920	-2.11537
5	0.38462	-0.29338	0.14000	0.43636	0.05769	0.12059	-1.96611	-0.82928	-2.85263	-2.11537
6	0.46154	-0.09656	0.14000	0.51471	0.05882	0.12500	-1.96611	-0.66416	-2.83321	-2.07944
7	0.53846	0.09656	0.17657	0.52304	0.07143	0.13656	-1.73402	-0.64809	-2.63906	-1.99096
8	0.61538	0.29338	0.22581	0.58182	0.09111	0.14286	-1.48808	-0.54160	-2.39568	-1.94591
9	0.69231	0.50240	0.23636	0.66129	0.09111	0.20000	-1.44238	-0.41356	-2.39568	-1.60944
10	0.76923	0.73632	0.33058	0.69231	0.11429	0.26190	-1.10691	-0.36772	-2.16905	-1.33977
11	0.84615	1.02008	0.38235	0.75556	0.12397	0.60000	-0.96141	-0.28030	-2.08774	-0.51083
12	0.92308	1.42608	0.39706	0.75556	0.30882	0.63830	-0.92367	-0.28030	-1.17499	-0.44895

Table 5.24: Calculations For Lognormal Distribution Fit (Coliphage: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9	COL#10	COL#11
Rank	F	ϕ -1 (F)	C1/C0	C2/C0	C3/C0	C3/C2	ln(C1/C0)	ln(C2/C0)	ln(C3/C0)	ln(C3/C2)
1	0.07692	-1.42608	0.02111	0.20000	0.00111	0.00333	-3.85796	-1.60944	-6.80239	-5.70378
2	0.15385	-1.02008	0.02200	0.21667	0.00167	0.00400	-3.81671	-1.52940	-6.39693	-5.52146
3	0.23077	-0.73632	0.18333	0.22500	0.00222	0.00750	-1.69645	-1.49165	-6.10925	-4.89285
4	0.30769	-0.50240	0.18333	0.26667	0.00250	0.00800	-1.69645	-1.32176	-5.99146	-4.82831
5	0.38462	-0.29338	0.18333	0.27778	0.00273	0.00833	-1.69645	-1.28093	-5.90445	-4.78749
6	0.46154	-0.09656	0.18500	0.30000	0.00333	0.01250	-1.68740	-1.20397	-5.70378	-4.38203
7	0.53846	0.09656	0.20000	0.30000	0.00400	0.01333	-1.60944	-1.20397	-5.52146	-4.31749
8	0.61538	0.29338	0.20769	0.30769	0.00500	0.01750	-1.57170	-1.17865	-5.29832	-4.04555
9	0.69231	0.50240	0.21250	0.32500	0.00538	0.02308	-1.54881	-1.12393	-5.22421	-3.76892
10	0.76923	0.73632	0.22500	0.33333	0.00750	0.02308	-1.49165	-1.09861	-4.89285	-3.76892
11	0.84615	1.02008	0.22500	0.36364	0.00750	0.03333	-1.49165	-1.01160	-4.89285	-3.40120
12	0.92308	1.42608	0.23333	0.41667	0.01250	0.06250	-1.45529	-0.87547	-4.38203	-2.77259



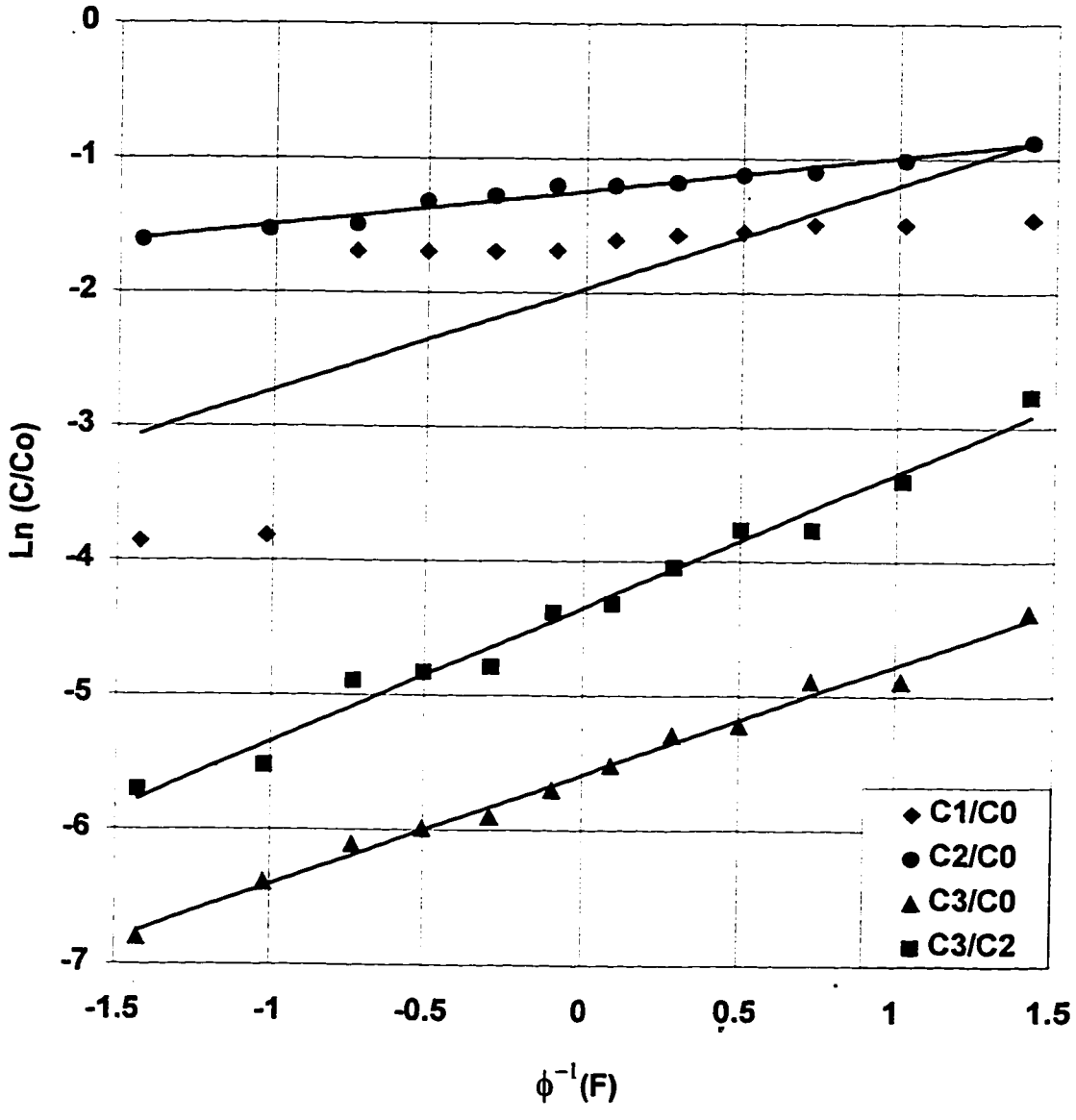
◆ y = 0.7398x - 1.788
R^2 = 0.9671

▲ y = 1.2594x - 2.8778
R^2 = 0.7447

■ y = 1.432x - 2.1234
R^2 = 0.7874

● y = 0.4928x - 0.7544
R^2 = 0.926

Figure 5.35 : Lognormal Distribution Fit for Coliphage Removal During Phase I



◆ y = 0.7652x - 1.9683
R^2 = 0.7483

▲ y = 0.8151x - 5.5933
R^2 = 0.9905

■ y = 0.9998x - 4.3492
R^2 = 0.981

● y = 0.2515x - 1.2441
R^2 = 0.9705

Figure 5.36 : Lognormal Distribution Fit for Coliphage Removal During Phase II

tables for the different indicator microorganisms are given in Tables. 5.26-5.38. Their respective plots are given in Figures 5.37 to 5.48. It is interesting to note that the probability lines for the treatment alternatives show a very sharp transition followed by a flat. This is attributable to the fact that the slow sand filter has a base level of microbial removals, which is achievable most of the time. Prechlorination merely tends to shift the curve towards the right, but follows essentially the same trend. However during the 15mg/l chlorination phase it is observed that the transition is virtually non-existent. This implies that there little variability in the removal rates, till a particular level is reached, after which no improvement is possible.

5.4.1.2 Step 2: Factor of Interaction

Using the CDF obtained for various indicator organisms, the values of $P(R_P \leq x_i)$ was obtained for all the treatment alternatives. This was done by selecting a desired removal level R_P, and the probability of its being met by the treatment alternative x_i was found by using the CDFs obtained in the first step.

The synergistic factor was found by substituting the probabilities of achieving safe levels in the equation

$$\lambda = \left[\frac{P(R_P \leq x1)}{P(R_P \leq x3)} + \frac{P(R_P \leq x2)}{P(R_P \leq x3)} \right]$$

Table 5.25: Calculations For Factor Of Interaction "λ" (Standard Plate Count: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDF Data)	y = 0.3062x - 2.1428	y = 1.1596x - 2.5074	y = 1.5139x - 4.8792	y = 1.0384x - 2.3716	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	0.21122	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.00739	9.01303	0.00063	0.00007	0.00000	0.00007
99.000	-4.60517	0.00000	3.52218	57.18198	1.57391	0.02752	0.00000	0.02752
99.000	-4.60517	0.00000	3.52218	57.18198	1.57391	0.02752	0.00000	0.02752
98.000	-3.91202	0.00000	11.28904	73.85445	6.89764	0.09340	0.00000	0.09340
97.000	-3.50656	0.00039	19.44427	81.77154	13.71998	0.16778	0.00000	0.16779
96.000	-3.21888	0.02111	26.97554	86.36180	20.72661	0.24000	0.00024	0.24024
95.000	-2.99573	0.25977	33.68333	89.32716	27.39027	0.30663	0.00291	0.30954
94.000	-2.81341	1.40001	39.59311	91.38024	33.52461	0.36687	0.01532	0.38219
93.000	-2.65926	4.53037	44.79038	92.87264	39.08815	0.42088	0.04878	0.46966
92.000	-2.52573	10.47974	49.36945	93.99763	44.10021	0.46916	0.11149	0.58065
90.000	-2.30259	30.02985	57.00987	95.56197	52.64954	0.55095	0.31424	0.86519
88.000	-2.12026	52.94319	63.07549	96.58032	59.56262	0.61672	0.54818	1.16489
85.000	-1.89712	78.95846	70.06549	97.55694	67.61407	0.69307	0.80936	1.50243
80.000	-1.60944	95.97318	78.06447	98.46070	76.85188	0.78053	0.97474	1.75527
75.000	-1.38629	99.34073	83.31789	98.94788	82.86564	0.83747	1.00397	1.84144
70.000	-1.20397	99.89513	86.95002	99.24016	86.95885	0.87625	1.00660	1.88285
65.000	-1.04982	99.98289	89.56170	99.42884	89.84729	0.90363	1.00557	1.90921
60.000	-0.91629	99.99707	91.49868	99.55735	91.94664	0.92355	1.00442	1.92797
55.000	-0.79851	99.99947	92.97176	99.64856	93.51036	0.93840	1.00352	1.94192
50.000	-0.69315	99.99990	94.11558	99.71545	94.69943	0.94970	1.00285	1.95255
45.000	-0.59784	99.99998	95.01946	99.76582	95.61976	0.95844	1.00235	1.96079
40.000	-0.51083	100.00000	95.74452	99.80460	96.34306	0.96532	1.00196	1.96727
35.000	-0.43078	100.00000	96.33377	99.83503	96.91918	0.97079	1.00165	1.97245
30.000	-0.35667	100.00000	96.81814	99.85928	97.38353	0.97521	1.00141	1.97662
25.000	-0.28768	100.00000	97.22034	99.87889	97.76175	0.97880	1.00121	1.98002
20.000	-0.22314	100.00000	97.55732	99.89493	98.07273	0.98176	1.00105	1.98281
15.000	-0.16252	100.00000	97.84195	99.90820	98.33062	0.98421	1.00092	1.98513
10.000	-0.10536	100.00000	98.08411	99.91929	98.54613	0.98626	1.00081	1.98707
5.000	-0.05129	100.00000	98.29152	99.92862	98.72750	0.98798	1.00071	1.98869
0.000	0.00000	100.00000	98.47024	99.93655	98.88113	0.98944	1.00063	1.99007

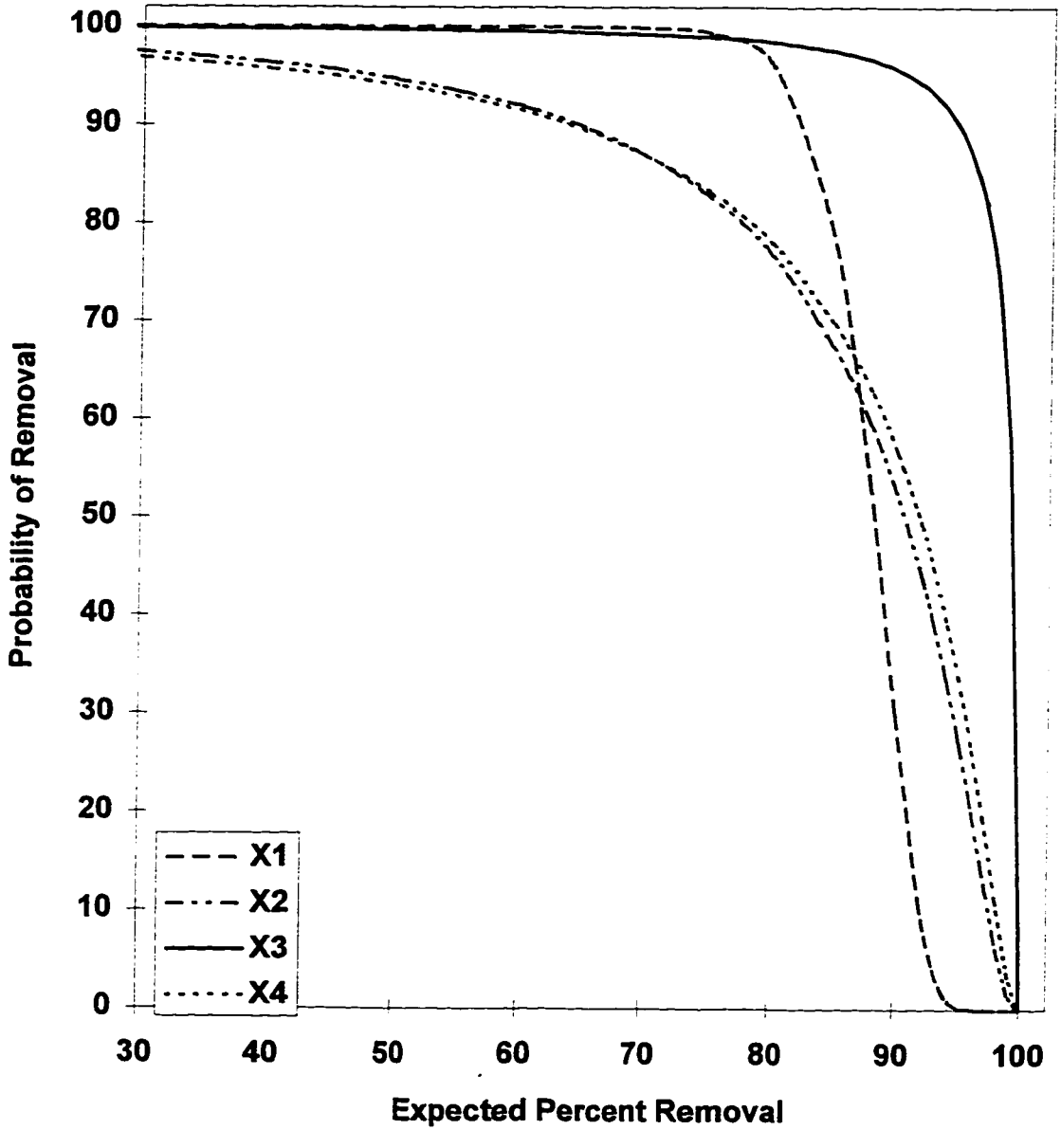


Fig 5.37 : Probability Plot for Removal of Standard Plate Counts During Phase I

Table 5.26: Calculations For Factor Of Interaction "λ" (Standard Plate Count: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y=0.3942x-2.3599	y=0.4036x-1.9177	y=1.0854x-8.3212	y=1.2486x-8.4035	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	20.63412	1.22884	0.05955	0.00000	0.05955
99.900	-6.90776	0.00000	0.00000	90.35817	34.31592	0.37978	0.00000	0.37978
99.000	-4.60517	0.00000	0.00000	99.96910	92.51054	0.92539	0.00000	0.92539
99.000	-4.60517	0.00000	0.00000	99.96910	92.51054	0.92539	0.00000	0.92539
98.000	-3.91202	0.00412	0.00004	99.99757	97.70013	0.97703	0.00004	0.97707
97.000	-3.50656	0.18140	0.00413	99.99954	98.98337	0.98984	0.00181	0.99165
96.000	-3.21888	1.46645	0.06323	99.99987	99.46224	0.99462	0.01466	1.00929
95.000	-2.99573	5.33756	0.37809	99.99995	99.68262	0.99683	0.05338	1.05020
94.000	-2.81341	12.49776	1.32330	99.99998	99.79817	0.99798	0.12498	1.12296
93.000	-2.65926	22.38031	3.30780	99.99999	99.86445	0.99864	0.22380	1.22245
92.000	-2.52573	33.69976	6.59678	100.00000	99.90508	0.99905	0.33700	1.33605
90.000	-2.30259	55.78007	17.01355	100.00000	99.94890	0.99949	0.55780	1.55729
88.000	-2.12026	72.83751	30.78718	100.00000	99.96986	0.99970	0.72838	1.72807
85.000	-1.89712	87.97970	52.03338	100.00000	99.98464	0.99985	0.87980	1.87964
80.000	-1.60944	97.15293	77.75012	100.00000	99.99383	0.99994	0.97153	1.97147
75.000	-1.38629	99.32411	90.60243	100.00000	99.99707	0.99997	0.99324	1.99321
70.000	-1.20397	99.83178	96.15032	100.00000	99.99844	0.99998	0.99832	1.99830
65.000	-1.04982	99.95553	98.42360	100.00000	99.99910	0.99999	0.99956	1.99955
60.000	-0.91629	99.98749	99.34528	100.00000	99.99944	0.99999	0.99987	1.99987
55.000	-0.79851	99.99627	99.72230	100.00000	99.99964	1.00000	0.99996	1.99996
50.000	-0.69315	99.99882	99.87936	100.00000	99.99976	1.00000	0.99999	1.99999
45.000	-0.59784	99.99961	99.94626	100.00000	99.99983	1.00000	1.00000	1.99999
40.000	-0.51083	99.99986	99.97546	100.00000	99.99988	1.00000	1.00000	2.00000
35.000	-0.43078	99.99995	99.98852	100.00000	99.99991	1.00000	1.00000	2.00000
30.000	-0.35667	99.99998	99.99451	100.00000	99.99994	1.00000	1.00000	2.00000
25.000	-0.28768	99.99999	99.99731	100.00000	99.99995	1.00000	1.00000	2.00000
20.000	-0.22314	100.00000	99.99866	100.00000	99.99996	1.00000	1.00000	2.00000
15.000	-0.16252	100.00000	99.99932	100.00000	99.99997	1.00000	1.00000	2.00000
10.000	-0.10536	100.00000	99.99964	100.00000	99.99998	1.00000	1.00000	2.00000
5.000	-0.05129	100.00000	99.99981	100.00000	99.99998	1.00000	1.00000	2.00000
0.000	0.00000	100.00000	99.99990	100.00000	99.99999	1.00000	1.00000	2.00000

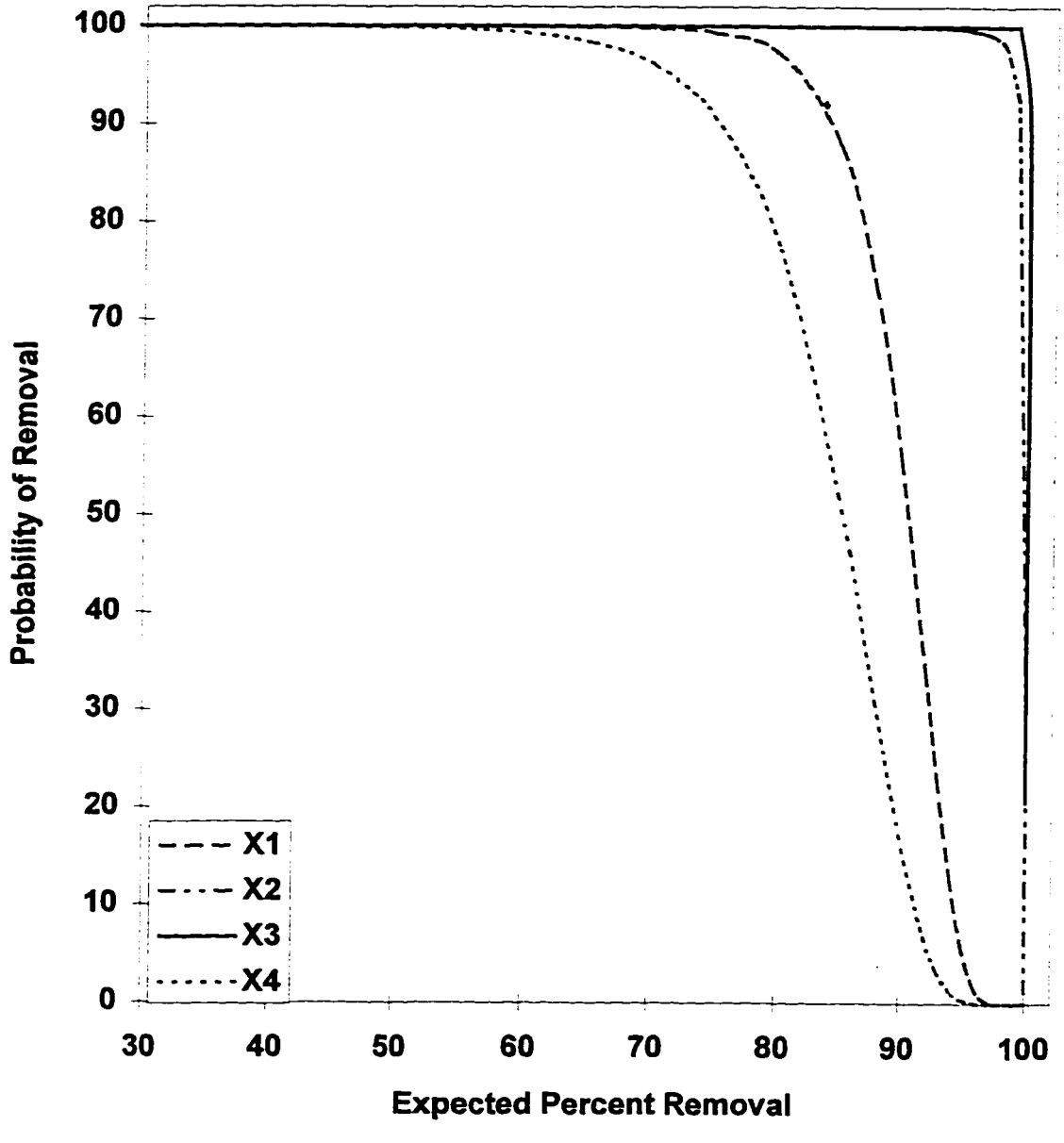


Fig 5.38 : Probability Plot for Removal of Standard Plate Counts During Phase II

Table 5.27: Calculations For Factor Of Interaction "λ" (Total Coliform: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y=0.7398x+1.788	y=1.1432x+2.1234	y=1.2594x+2.8778	y=0.4928x+0.7644	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00004	0.00002	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.04174	0.06874	0.00000	0.00000	0.00000	0.00000
99.000	-4.60517	0.00701	4.15407	8.50969	0.00000	0.00000	0.00082	0.00082
99.000	-4.60517	0.00701	4.15407	8.50969	0.00000	0.00000	0.00082	0.00082
98.000	-3.91202	0.20454	10.58256	20.57653	0.00000	0.00000	0.00994	0.00994
97.000	-3.50656	1.00895	16.70490	30.88009	0.00000	0.00000	0.03267	0.03267
96.000	-3.21888	2.65480	22.21366	39.32632	0.00003	0.00000	0.06751	0.06751
95.000	-2.99573	5.12858	27.12056	46.26969	0.00027	0.00001	0.11084	0.11085
94.000	-2.81341	8.28636	31.49559	52.03879	0.00147	0.00003	0.15923	0.15926
93.000	-2.65926	11.94588	35.41264	56.88814	0.00555	0.00010	0.20999	0.21009
92.000	-2.52573	15.93337	38.93722	61.00904	0.01626	0.00027	0.26116	0.26143
90.000	-2.30259	24.33480	45.02106	67.60700	0.08402	0.00124	0.35994	0.36119
88.000	-2.12026	32.66703	50.08738	72.62485	0.27888	0.00384	0.44981	0.45365
85.000	-1.89712	44.13689	56.27782	78.19184	1.02021	0.01305	0.56447	0.57752
80.000	-1.60944	59.53640	64.01695	84.30605	4.13650	0.04907	0.70619	0.75526
75.000	-1.38629	70.64324	69.66322	88.18525	9.98770	0.11326	0.80108	0.91434
70.000	-1.20397	78.50724	73.95823	90.80870	18.08100	0.19911	0.86453	1.06365
65.000	-1.04982	84.08136	77.32839	92.66751	27.44275	0.29614	0.90734	1.20349
60.000	-0.91629	88.06622	80.03728	94.03235	37.12623	0.39482	0.93655	1.33138
55.000	-0.79851	90.94724	82.25702	95.06326	46.43405	0.48845	0.95670	1.44516
50.000	-0.69315	93.05541	84.10493	95.86011	54.94594	0.57319	0.97074	1.54393
45.000	-0.59784	94.61659	85.66383	96.48798	62.46440	0.64738	0.98060	1.62799
40.000	-0.51083	95.78603	86.99382	96.99083	68.94409	0.71083	0.98758	1.69841
35.000	-0.43078	96.67156	88.13961	97.39921	74.43101	0.76418	0.99253	1.75671
30.000	-0.35667	97.34893	89.13513	97.73494	79.01875	0.80850	0.99605	1.80455
25.000	-0.28768	97.87202	90.00656	98.01391	82.81994	0.84498	0.99855	1.84353
20.000	-0.22314	98.27954	90.77447	98.24791	85.94913	0.87482	1.00032	1.87514
15.000	-0.16252	98.59966	91.45519	98.44587	88.51355	0.89911	1.00156	1.90067
10.000	-0.10536	98.85306	92.06186	98.61461	90.60881	0.91882	1.00242	1.92124
5.000	-0.05129	99.05510	92.60518	98.75944	92.31752	0.93477	1.00299	1.93777
0.000	0.00000	99.21727	93.09390	98.88453	93.70960	0.94767	1.00336	1.95103

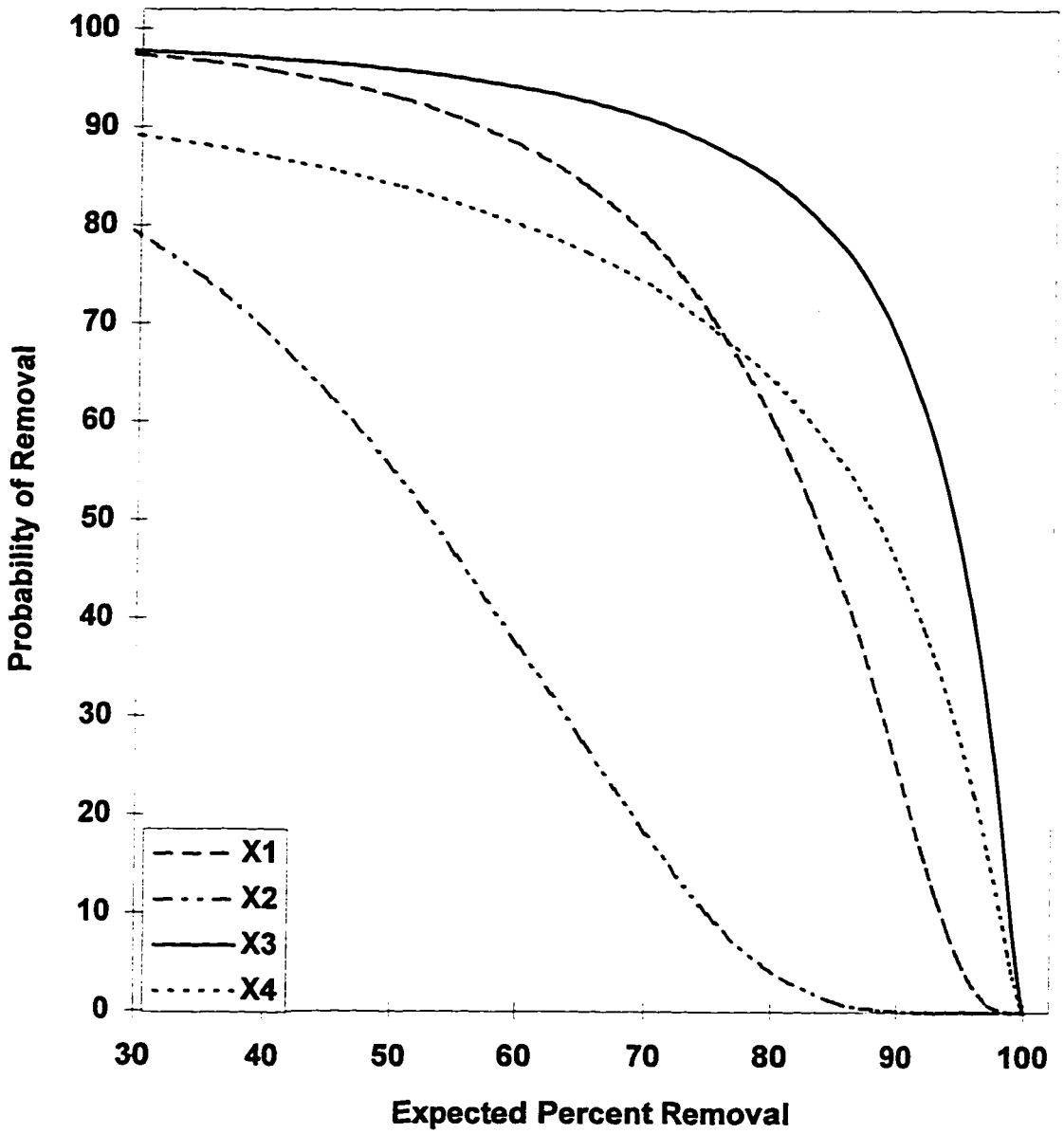


Fig 5.39 : Probability Plot for Removal of Total Coliform During Phase I

Table 5.28: Calculations For Factor Of Interaction "λ" (Total Coliform: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y=0.2369x-1.7203	y=0.8336x-2.6378	y=0.829x-9.9336	y=0.654x-7.3958	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	56.02408	0.27642	0.00493	0.00000	0.00493
99.900	-6.90776	0.00000	0.00001	99.83003	77.22406	0.77356	0.00000	0.77356
99.000	-4.60517	0.00000	0.65682	100.00000	99.99901	0.99999	0.00000	0.99999
99.000	-4.60517	0.00000	0.65682	100.00000	99.99901	0.99999	0.00000	0.99999
98.000	-3.91202	0.00000	4.96209	100.00000	99.99999	1.00000	0.00000	1.00000
97.000	-3.50656	0.00000	12.25898	100.00000	100.00000	1.00000	0.00000	1.00000
96.000	-3.21888	0.00000	20.69557	100.00000	100.00000	1.00000	0.00000	1.00000
95.000	-2.99573	0.00000	29.13850	100.00000	100.00000	1.00000	0.00000	1.00000
94.000	-2.81341	0.00020	37.04632	100.00000	100.00000	1.00000	0.00000	1.00000
93.000	-2.65926	0.00369	44.20769	100.00000	100.00000	1.00000	0.00004	1.00004
92.000	-2.52573	0.03371	50.57769	100.00000	100.00000	1.00000	0.00034	1.00034
90.000	-2.30259	0.69869	61.10924	100.00000	100.00000	1.00000	0.00699	1.00699
88.000	-2.12026	4.56747	69.17734	100.00000	100.00000	1.00000	0.04567	1.04567
85.000	-1.89712	22.77156	77.89258	100.00000	100.00000	1.00000	0.22772	1.22772
80.000	-1.60944	68.00970	86.72913	100.00000	100.00000	1.00000	0.68010	1.68010
75.000	-1.38629	92.07155	91.64165	100.00000	100.00000	1.00000	0.92072	1.92072
70.000	-1.20397	98.53534	94.52097	100.00000	100.00000	1.00000	0.98535	1.98535
65.000	-1.04982	99.76741	96.28696	100.00000	100.00000	1.00000	0.99767	1.99767
60.000	-0.91629	99.96554	97.41239	100.00000	100.00000	1.00000	0.99966	1.99966
55.000	-0.79851	99.99501	98.15326	100.00000	100.00000	1.00000	0.99995	1.99995
50.000	-0.69315	99.99927	98.65469	100.00000	100.00000	1.00000	0.99999	1.99999
45.000	-0.59784	99.99989	99.00230	100.00000	100.00000	1.00000	1.00000	2.00000
40.000	-0.51083	99.99998	99.24837	100.00000	100.00000	1.00000	1.00000	2.00000
35.000	-0.43078	100.00000	99.42579	100.00000	100.00000	1.00000	1.00000	2.00000
30.000	-0.35667	100.00000	99.55583	100.00000	100.00000	1.00000	1.00000	2.00000
25.000	-0.28768	100.00000	99.65254	100.00000	100.00000	1.00000	1.00000	2.00000
20.000	-0.22314	100.00000	99.72542	100.00000	100.00000	1.00000	1.00000	2.00000
15.000	-0.16252	100.00000	99.78100	100.00000	100.00000	1.00000	1.00000	2.00000
10.000	-0.10536	100.00000	99.82385	100.00000	100.00000	1.00000	1.00000	2.00000
5.000	-0.05129	100.00000	99.85721	100.00000	100.00000	1.00000	1.00000	2.00000
0.000	0.00000	100.00000	99.88342	100.00000	100.00000	1.00000	1.00000	2.00000

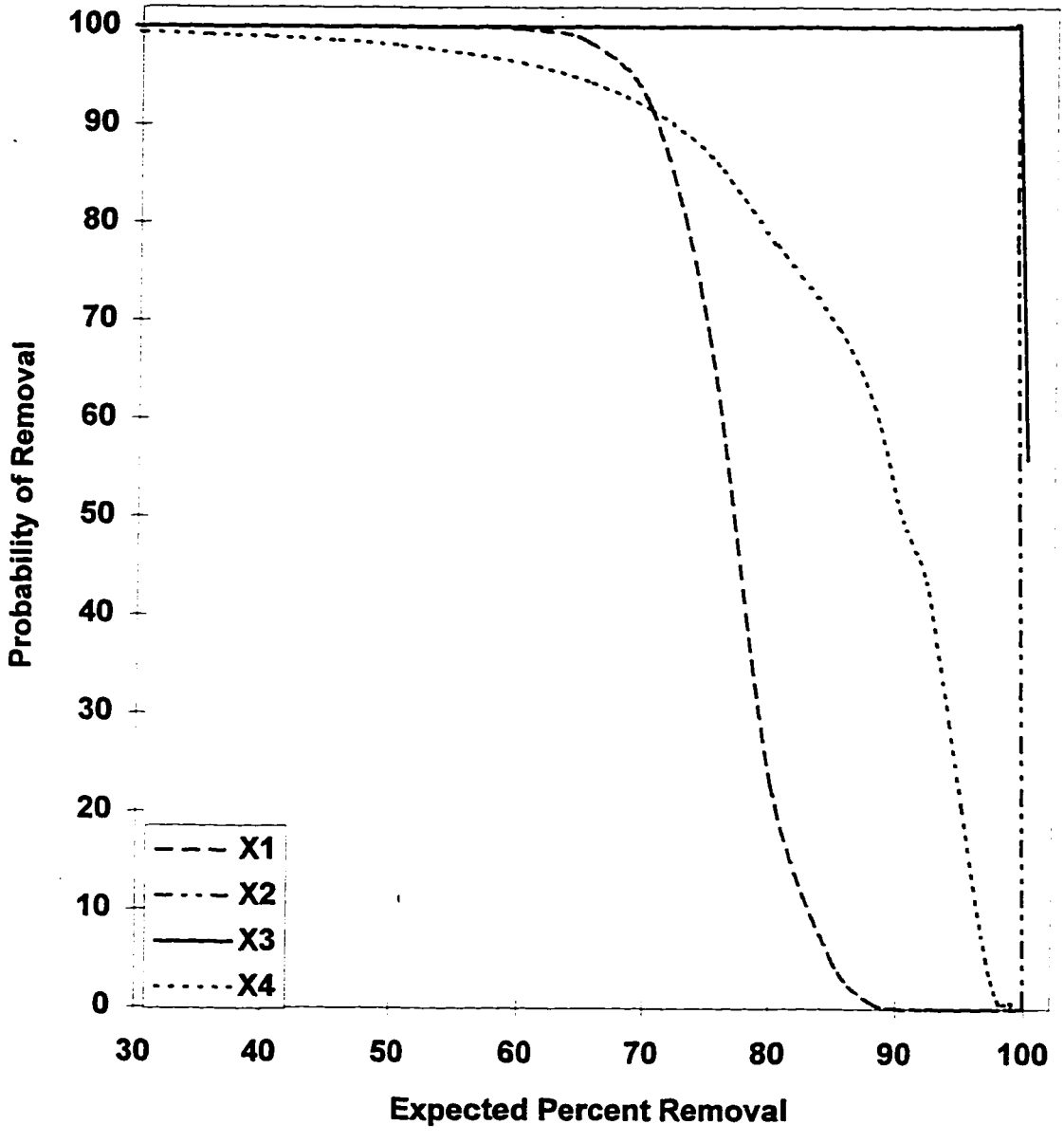


Fig 5.40 : Probability Plot for Removal of Total Coliform During Phase II

Table 5.29: Calculations For Factor Of Interaction "λ" (Fecal Coliform: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs =>)	y = 0.5817x + 2.0807	y = 0.6779x + 2.1403	y = 0.7739x + 4.1982	y = 0.6788x + 2.0579	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.00000	0.02317	0.00000	0.00000	0.00000	0.00000
99.000	-4.60517	0.00099	0.01385	29.94895	0.00860	0.00029	0.00003	0.00032
99.000	-4.60517	0.00099	0.01385	29.94895	0.00860	0.00029	0.00003	0.00032
98.000	-3.91202	0.09841	0.44804	64.42288	0.31106	0.00483	0.00153	0.00636
97.000	-3.50656	0.79814	2.19299	81.42615	1.62354	0.01994	0.00980	0.02974
96.000	-3.21888	2.72042	5.57987	89.71431	4.31950	0.04815	0.03032	0.07847
95.000	-2.99573	6.09984	10.34950	93.98811	8.28700	0.08817	0.06490	0.15307
94.000	-2.81341	10.77998	16.03708	96.32220	13.19055	0.13694	0.11192	0.24886
93.000	-2.65926	16.40884	22.19748	97.66247	18.66427	0.19111	0.16802	0.35913
92.000	-2.52573	22.59898	28.48264	98.46561	24.39605	0.24776	0.22951	0.47727
90.000	-2.30259	35.38318	40.54001	99.28459	35.75980	0.36017	0.35638	0.71656
88.000	-2.12026	47.33448	51.17897	99.63737	46.16440	0.46332	0.47507	0.93839
85.000	-1.89712	62.18178	64.00997	99.85271	59.19017	0.59277	0.62273	1.21551
80.000	-1.60944	78.71161	78.32153	99.95887	74.41682	0.74447	0.78744	1.53191
75.000	-1.38629	87.97177	86.69882	99.98601	83.76835	0.83780	0.87984	1.71764
70.000	-1.20397	93.07911	91.63939	99.99453	89.50018	0.89505	0.93084	1.82589
65.000	-1.04982	95.92660	94.61494	99.99763	93.06525	0.93067	0.95929	1.88996
60.000	-0.91629	97.54606	96.45088	99.99889	95.32665	0.95328	0.97547	1.92875
55.000	-0.79851	98.48812	97.61110	99.99944	96.79082	0.96791	0.98489	1.95280
50.000	-0.69315	99.04872	98.36097	99.99970	97.75782	0.97758	0.99049	1.96807
45.000	-0.59784	99.38965	98.85577	99.99984	98.40846	0.98409	0.99390	1.97798
40.000	-0.51083	99.60128	99.18852	99.99991	98.85384	0.98854	0.99601	1.98455
35.000	-0.43078	99.73518	99.41619	99.99994	99.16360	0.99164	0.99735	1.98899
30.000	-0.35667	99.82140	99.57446	99.99997	99.38219	0.99382	0.99821	1.99204
25.000	-0.28768	99.87783	99.68608	99.99998	99.53854	0.99539	0.99878	1.99416
20.000	-0.22314	99.91533	99.76585	99.99999	99.65175	0.99652	0.99915	1.99567
15.000	-0.16252	99.94061	99.82357	99.99999	99.73468	0.99735	0.99941	1.99675
10.000	-0.10536	99.95787	99.86581	99.99999	99.79608	0.99796	0.99958	1.99754
5.000	-0.05129	99.96979	99.89704	100.00000	99.84197	0.99842	0.99970	1.99812
0.000	0.00000	99.97813	99.92036	100.00000	99.87660	0.99877	0.99978	1.99855

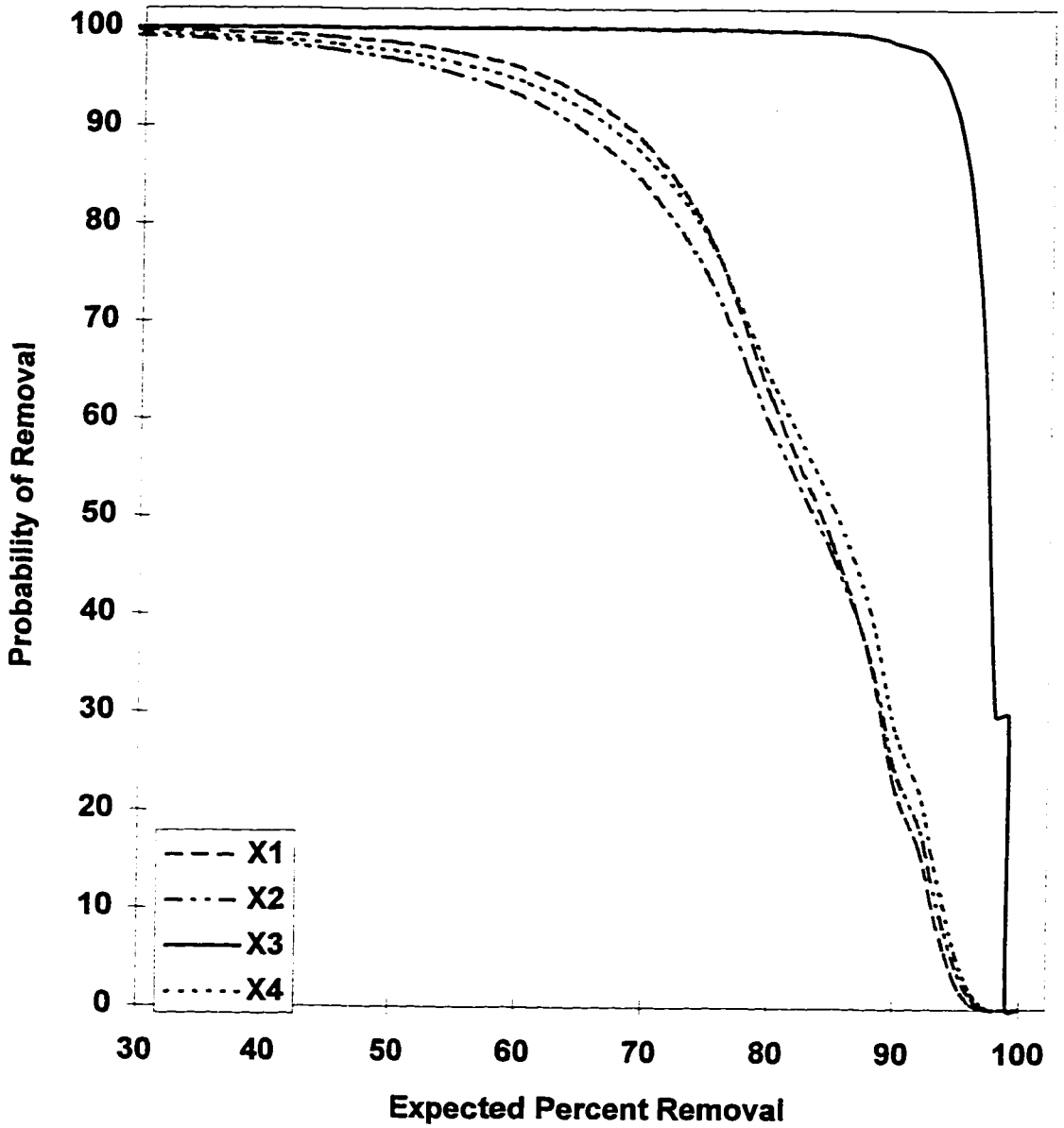


Fig 5.41 : Probability Plot for Removal of Fecal Coliform During Phase I

Table 5.30: Calculations For Factor Of Interaction "λ" (Fecal Colifrom: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDF$_{Rp}$)	y = 0.2578x - 1.6522	y = 0.8572x - 2.3931	y = 0.8167x - 10.217	y = 0.8097x + 7.9238	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	89.11363	4.34103	0.04871	0.00000	0.04871
99.900	-6.90776	0.00000	0.00001	99.99746	87.10436	0.87107	0.00000	0.87107
99.000	-4.60517	0.00000	0.49318	100.00000	99.99648	0.99996	0.00000	0.99996
99.000	-4.60517	0.00000	0.49318	100.00000	99.99648	0.99996	0.00000	0.99996
98.000	-3.91202	0.00000	3.82007	100.00000	99.99993	1.00000	0.00000	1.00000
97.000	-3.50656	0.00000	9.69810	100.00000	100.00000	1.00000	0.00000	1.00000
96.000	-3.21888	0.00000	16.76882	100.00000	100.00000	1.00000	0.00000	1.00000
95.000	-2.99573	0.00001	24.10203	100.00000	100.00000	1.00000	0.00000	1.00000
94.000	-2.81341	0.00033	31.19503	100.00000	100.00000	1.00000	0.00000	1.00000
93.000	-2.65926	0.00469	37.80907	100.00000	100.00000	1.00000	0.00000	1.00000
92.000	-2.52573	0.03516	43.85198	100.00000	100.00000	1.00000	0.00005	1.00005
90.000	-2.30259	0.58208	54.20477	100.00000	100.00000	1.00000	0.00035	1.00035
88.000	-2.12026	3.47153	62.48667	100.00000	100.00000	1.00000	0.00582	1.00582
85.000	-1.89712	17.10463	71.85721	100.00000	100.00000	1.00000	0.03472	1.03472
80.000	-1.60944	56.58716	81.96972	100.00000	100.00000	1.00000	0.17105	1.17105
75.000	-1.38629	84.88331	87.99082	100.00000	100.00000	1.00000	0.56587	1.56587
70.000	-1.20397	95.89530	91.73130	100.00000	100.00000	1.00000	0.84883	1.84883
65.000	-1.04982	99.02703	94.14488	100.00000	100.00000	1.00000	0.95895	1.95895
60.000	-0.91629	99.78452	95.75403	100.00000	100.00000	1.00000	0.99027	1.99027
55.000	-0.79851	99.95359	96.85738	100.00000	100.00000	1.00000	0.99785	1.99785
50.000	-0.69315	99.99004	97.63245	100.00000	100.00000	1.00000	0.99954	1.99954
45.000	-0.59784	99.99784	98.18849	100.00000	100.00000	1.00000	0.99990	1.99990
40.000	-0.51083	99.99952	98.59484	100.00000	100.00000	1.00000	0.99998	1.99998
35.000	-0.43078	99.99989	98.89667	100.00000	100.00000	1.00000	1.00000	2.00000
30.000	-0.35667	99.99997	99.12415	100.00000	100.00000	1.00000	1.00000	2.00000
25.000	-0.28768	99.99999	99.29784	100.00000	100.00000	1.00000	1.00000	2.00000
20.000	-0.22314	100.00000	99.43203	100.00000	100.00000	1.00000	1.00000	2.00000
15.000	-0.16252	100.00000	99.53682	100.00000	100.00000	1.00000	1.00000	2.00000
10.000	-0.10536	100.00000	99.61944	100.00000	100.00000	1.00000	1.00000	2.00000
5.000	-0.05129	100.00000	99.68517	100.00000	100.00000	1.00000	1.00000	2.00000
0.000	0.00000	100.00000	99.73789	100.00000	100.00000	1.00000	1.00000	2.00000

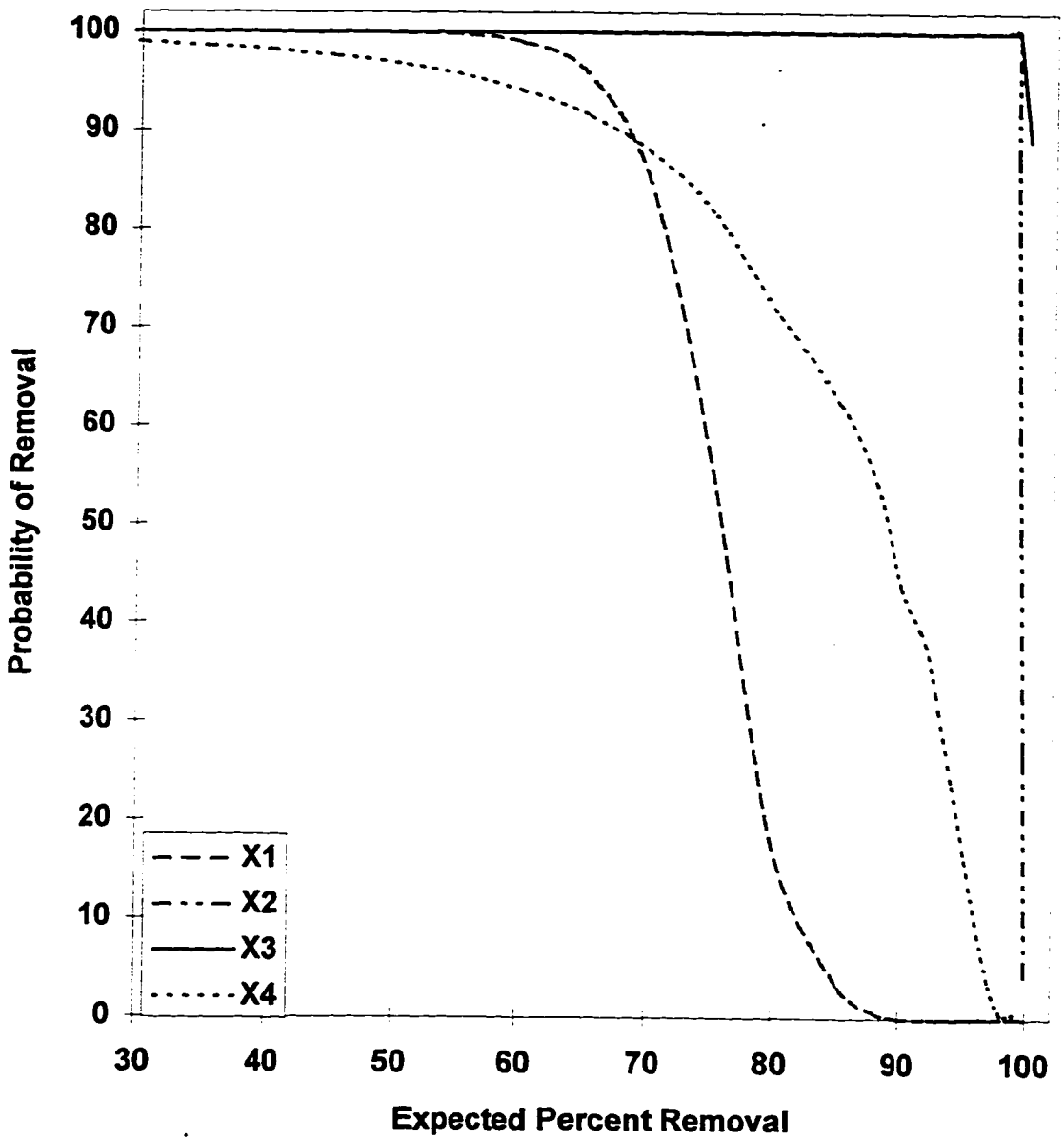


Fig 5.42 : Probability Plot for Removal of Fecal Coliform During Phase II

Table 5.31: Calculations For Factor Of Interaction "λ" (Fecal Streptococcus: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y = 0.6546x + 1.8678	y = 0.9991x + 2.4111	y = 0.9765x + 4.0368	y = 1.0005x + 1.6247	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.00034	0.16355	0.00001	0.00004	0.00000	0.00004
99.000	-4.60517	0.00165	1.40443	27.99222	0.14461	0.00517	0.00006	0.00523
99.000	-4.60517	0.00165	1.40443	27.99222	0.14461	0.00517	0.00006	0.00523
98.000	-3.91202	0.09931	6.65131	55.04332	1.11218	0.02021	0.00180	0.02201
97.000	-3.50656	0.67012	13.64421	70.60834	2.99915	0.04248	0.00949	0.05197
96.000	-3.21888	2.10051	20.94003	79.85868	5.55376	0.06954	0.02630	0.09585
95.000	-2.99573	4.52721	27.92204	85.65841	8.52893	0.09957	0.05285	0.15242
94.000	-2.81341	7.86796	34.35944	89.46798	11.73938	0.13121	0.08794	0.21915
93.000	-2.65926	11.92945	40.19189	92.06810	15.05580	0.16353	0.12957	0.29310
92.000	-2.52573	16.48962	45.43288	93.89974	18.39062	0.19585	0.17561	0.37146
90.000	-2.30259	26.31557	54.32452	96.20450	24.90296	0.25885	0.27354	0.53239
88.000	-2.12026	36.12488	61.45119	97.50976	31.01886	0.31811	0.37047	0.68858
85.000	-1.89712	49.43201	69.65289	98.57433	39.27019	0.39838	0.50147	0.89985
80.000	-1.60944	66.46691	78.88347	99.35179	50.60854	0.50939	0.66901	1.17839
75.000	-1.38629	77.81992	84.74903	99.66688	59.41705	0.59616	0.78080	1.37696
70.000	-1.20397	85.19074	88.65176	99.81340	66.29460	0.66419	0.85350	1.51769
65.000	-1.04982	89.97515	91.34805	99.88852	71.72159	0.71802	0.90076	1.61877
60.000	-0.91629	93.11123	93.26934	99.92998	76.05446	0.76108	0.93176	1.69284
55.000	-0.79851	95.19496	94.67412	99.95421	79.55354	0.79590	0.95239	1.74829
50.000	-0.69315	96.60004	95.72384	99.96904	82.40958	0.82435	0.96630	1.79065
45.000	-0.59784	97.56160	96.52301	99.97848	84.76366	0.84782	0.97583	1.82365
40.000	-0.51083	98.22906	97.14136	99.98467	86.72140	0.86735	0.98244	1.84979
35.000	-0.43078	98.69867	97.62661	99.98886	88.36280	0.88373	0.98710	1.87082
30.000	-0.35667	99.03329	98.01221	99.99176	89.74922	0.89757	0.99041	1.88798
25.000	-0.28768	99.27458	98.32205	99.99380	90.92824	0.90934	0.99281	1.90215
20.000	-0.22314	99.45049	98.57353	99.99528	91.93714	0.91941	0.99455	1.91397
15.000	-0.16252	99.58009	98.77948	99.99635	92.80540	0.92809	0.99584	1.92393
10.000	-0.10536	99.67648	98.94954	99.99715	93.55659	0.93559	0.99679	1.93239
5.000	-0.05129	99.74883	99.09100	99.99775	94.20966	0.94212	0.99751	1.93963
0.000	0.00000	99.80360	99.20950	99.99821	94.78002	0.94782	0.99805	1.94587

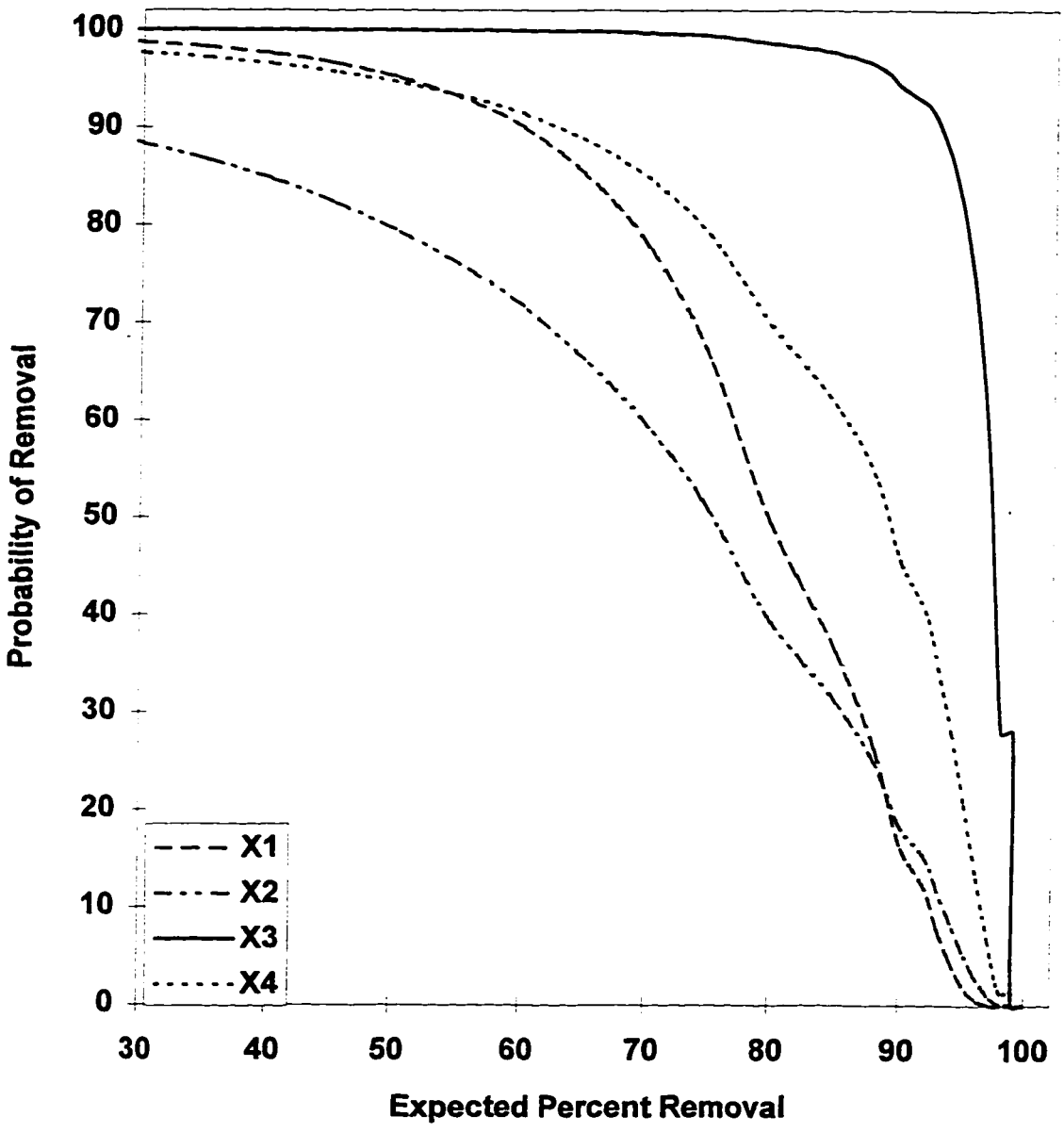


Fig 5.43 : Probability Plot for Removal of Fecal Streptococcus During Phase I

Table 5.32: Calculations For Factor Of Interaction "λ" (Fecal Streptococcus: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y = 0.3979x + 2.1062	y = 0.7499x + 1.5476	y = 1.1844x + 8.0931	y = 0.721x + 6.5455	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	17.27646	0.01095	0.00063	0.00000	0.00063
99.900	-6.90776	0.00000	0.00000	84.15377	30.76809	0.36562	0.00000	0.36562
99.000	-4.60517	0.00000	0.00228	99.83846	99.64398	0.99805	0.00000	0.99805
99.000	-4.60517	0.00000	0.00228	99.83846	99.64398	0.99805	0.00000	0.99805
98.000	-3.91202	0.00028	0.08081	99.97923	99.98701	1.00008	0.00000	1.00008
97.000	-3.50656	0.02163	0.44969	99.99461	99.99875	1.00004	0.00022	1.00026
96.000	-3.21888	0.25841	1.29181	99.99807	99.99980	1.00002	0.00258	1.00260
95.000	-2.99573	1.26900	2.67352	99.99916	99.99996	1.00001	0.01269	1.01270
94.000	-2.81341	3.77546	4.57082	99.99959	99.99999	1.00000	0.03775	1.03776
93.000	-2.65926	8.22725	6.91155	99.99978	100.00000	1.00000	0.08227	1.08227
92.000	-2.52573	14.58598	9.60580	99.99987	100.00000	1.00000	0.14586	1.14586
90.000	-2.30259	31.08106	15.70200	99.99995	100.00000	1.00000	0.31081	1.31081
88.000	-2.12026	48.59025	22.25369	99.99998	100.00000	1.00000	0.48590	1.48590
85.000	-1.89712	70.03678	32.05760	99.99999	100.00000	1.00000	0.70037	1.70037
80.000	-1.60944	89.40685	46.71398	100.00000	100.00000	1.00000	0.89407	1.89407
75.000	-1.38629	96.47950	58.51564	100.00000	100.00000	1.00000	0.96479	1.96479
70.000	-1.20397	98.83193	67.66066	100.00000	100.00000	1.00000	0.98832	1.98832
65.000	-1.04982	99.60332	74.65885	100.00000	100.00000	1.00000	0.99603	1.99603
60.000	-0.91629	99.86072	80.00663	100.00000	100.00000	1.00000	0.99861	1.99861
55.000	-0.79851	99.94927	84.10840	100.00000	100.00000	1.00000	0.99949	1.99949
50.000	-0.69315	99.98083	87.27364	100.00000	100.00000	1.00000	0.99981	1.99981
45.000	-0.59784	99.99249	89.73364	100.00000	100.00000	1.00000	0.99992	1.99992
40.000	-0.51083	99.99696	91.65985	100.00000	100.00000	1.00000	0.99997	1.99997
35.000	-0.43078	99.99873	93.17942	100.00000	100.00000	1.00000	0.99999	1.99999
30.000	-0.35667	99.99945	94.38695	100.00000	100.00000	1.00000	0.99999	1.99999
25.000	-0.28768	99.99976	95.35325	100.00000	100.00000	1.00000	1.00000	2.00000
20.000	-0.22314	99.99989	96.13170	100.00000	100.00000	1.00000	1.00000	2.00000
15.000	-0.16252	99.99995	96.76280	100.00000	100.00000	1.00000	1.00000	2.00000
10.000	-0.10536	99.99998	97.27753	100.00000	100.00000	1.00000	1.00000	2.00000
5.000	-0.05129	99.99999	97.69973	100.00000	100.00000	1.00000	1.00000	2.00000
0.000	0.00000	99.99999	98.04790	100.00000	100.00000	1.00000	1.00000	2.00000

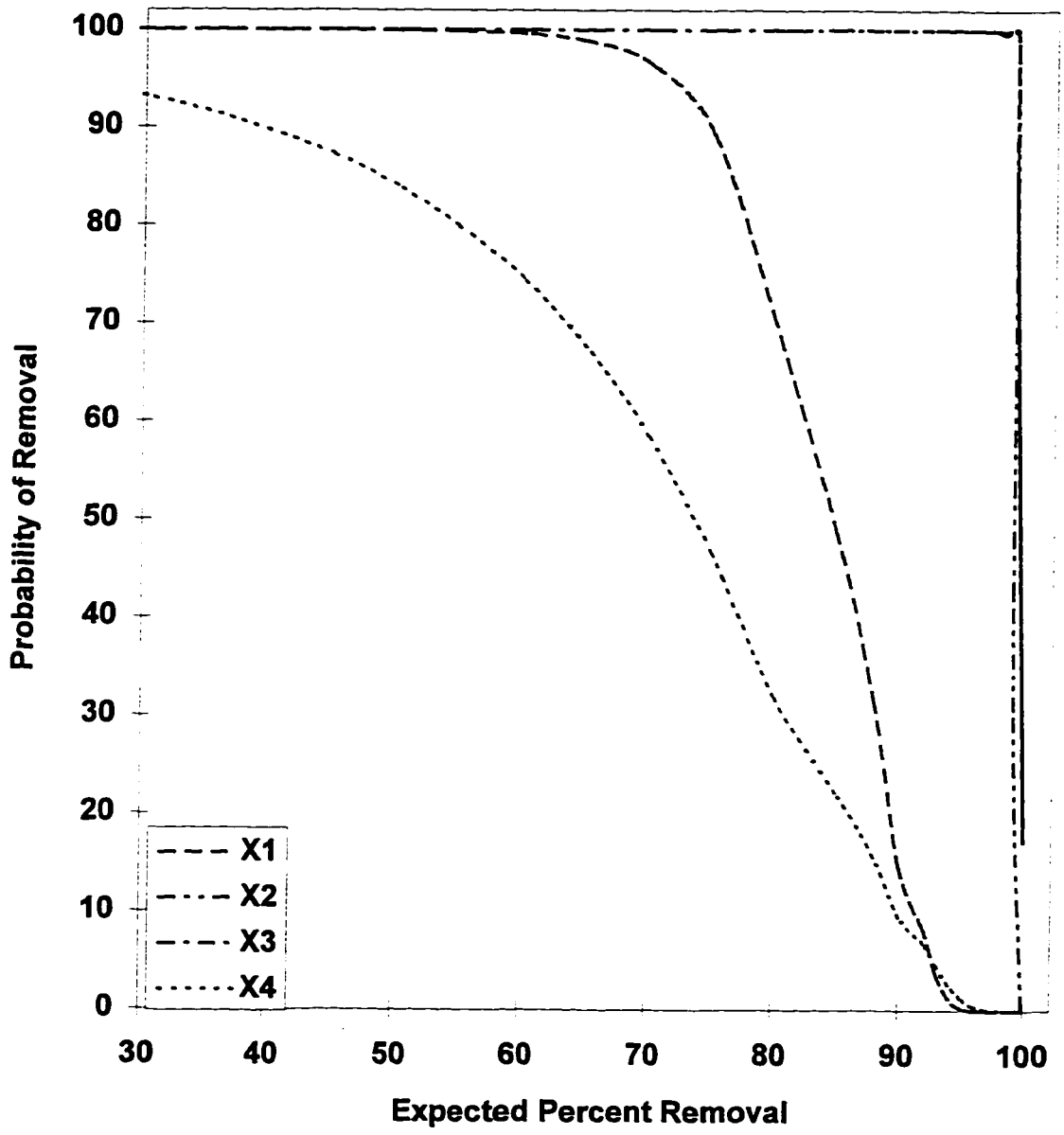


Fig 5.44 : Probability Plot for Removal of Fecal Streptococcus During Phase II

Table 5.33: Calculations For Factor Of Interaction "λ" (*Clostridium perfringens*: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs =>)	y = 0.698x - 1.6515	y = 0.6557x - 1.7248		y = 0.6384x - 2.3889	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
99.000	-4.60517	0.00004	0.00056	0.02587	0.00000	0.00000	0.00152	0.00152
99.000	-4.60517	0.00004	0.00056	0.02587	0.00000	0.00000	0.00152	0.00152
98.000	-3.91202	0.00784	0.04255	0.85200	0.00000	0.00000	0.00920	0.00920
97.000	-3.50656	0.09608	0.32905	3.99973	0.00000	0.00000	0.02402	0.02402
96.000	-3.21888	0.43833	1.13455	9.67856	0.00001	0.00000	0.04529	0.04529
95.000	-2.99573	1.22919	2.62943	17.09160	0.00008	0.00000	0.07192	0.07192
94.000	-2.81341	2.60083	4.84344	25.30378	0.00049	0.00002	0.10278	0.10280
93.000	-2.65926	4.59733	7.70594	33.59666	0.00201	0.00006	0.13684	0.13690
92.000	-2.52573	7.18815	11.09510	41.51447	0.00638	0.00015	0.17315	0.17330
90.000	-2.30259	13.81275	18.91121	55.37752	0.03731	0.00067	0.24943	0.25010
88.000	-2.12026	21.65536	27.32155	66.30481	0.13640	0.00206	0.32660	0.32866
85.000	-1.89712	34.06332	39.63512	77.94486	0.55808	0.00716	0.43702	0.44418
80.000	-1.60944	52.80377	56.98284	88.89497	2.58549	0.02908	0.59400	0.62309
75.000	-1.38629	67.12935	69.71604	94.18503	6.85996	0.07283	0.71274	0.78557
70.000	-1.20397	77.28825	78.64917	96.82796	13.32674	0.13763	0.79820	0.93584
65.000	-1.04982	84.28284	84.83542	98.20277	21.36471	0.21756	0.85825	1.07581
60.000	-0.91629	89.05478	89.12209	98.94648	30.18742	0.30509	0.90003	1.20512
55.000	-0.79851	92.31247	92.11246	99.36347	39.10376	0.39354	0.92904	1.32258
50.000	-0.69315	94.54881	94.21824	99.60493	47.61653	0.47805	0.94924	1.42729
45.000	-0.59784	96.09636	95.71671	99.74884	55.42383	0.55563	0.96338	1.51902
40.000	-0.51083	97.17710	96.79453	99.83686	62.37878	0.62481	0.97336	1.59817
35.000	-0.43078	97.93912	97.57802	99.89197	68.44486	0.68519	0.98045	1.66564
30,000	-0.35667	98.48161	98.15339	99.92719	73.65327	0.73707	0.98553	1.72260
25.000	-0.28768	98.87149	98.58006	99.95015	78.07362	0.78113	0.98921	1.77033
20.000	-0.22314	99.15426	98.89939	99.96536	81.79300	0.81821	0.99189	1.81010
15.000	-0.16252	99.36117	99.14049	99.97561	84.90277	0.84923	0.99385	1.84309
10.000	-0.10536	99.51383	99.32403	99.98262	87.49087	0.87506	0.99531	1.87037
5.000	-0.05129	99.62739	99.46484	99.98747	89.63777	0.89649	0.99640	1.89289
0.000	0.00000	99.71249	99.57366	99.99087	91.41469	0.91423	0.99722	1.91145

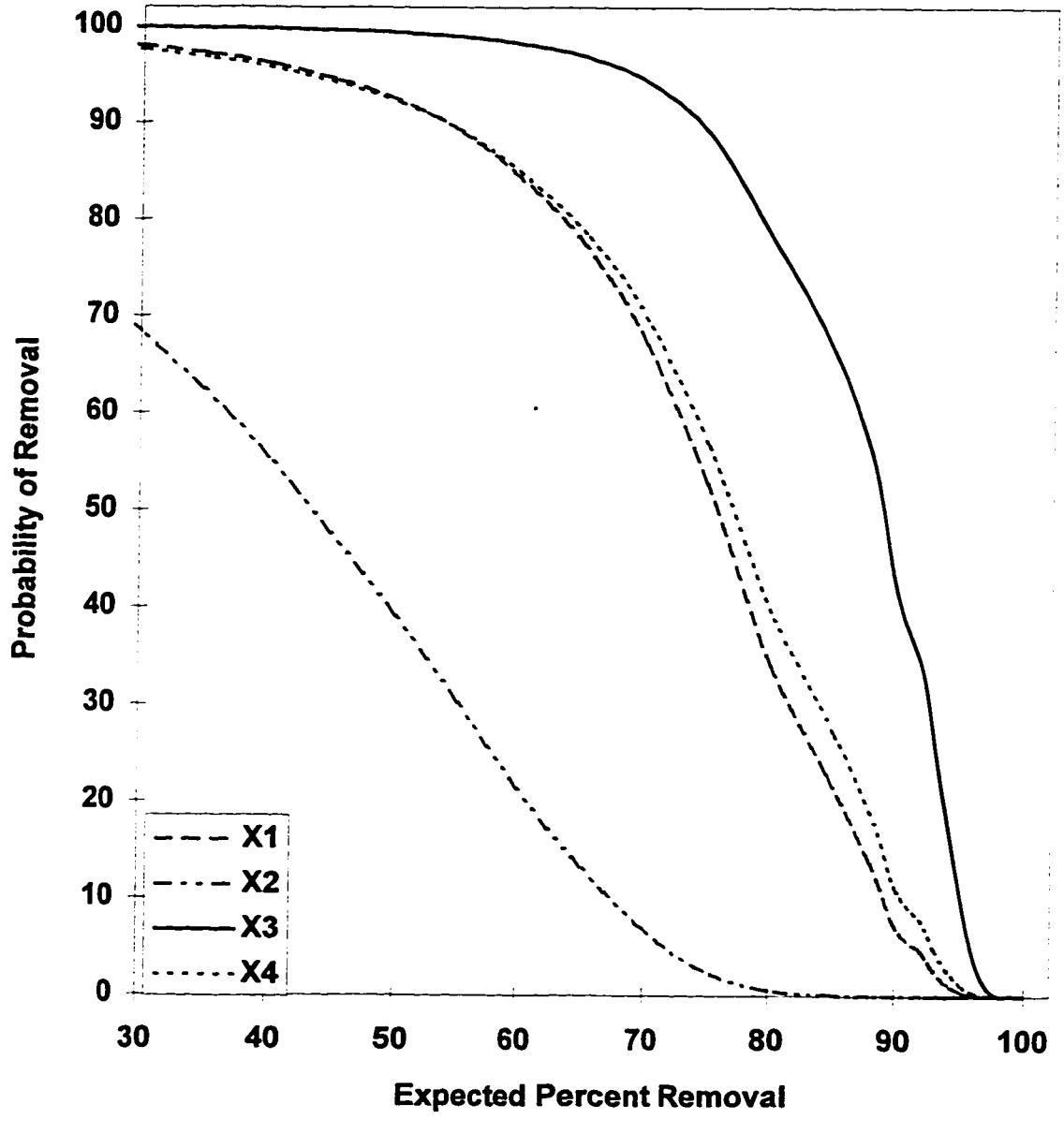


Fig 5.45 : Probability Plot for Removal of *Clostridium perfringens* During Phase I

Table 5.34: Calculations For Factor Of Interaction "λ" (*Clostridium perfringens*: Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs =>)	y = 0.1432x + 1.6207	y = 1.2577x + 2.461	y = 0.6389x + 4.2033	y = 1.2679x + 1.7423	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00000	0.00002	0.00000	0.00831	0.00000	0.00831
99.900	-6.90776	0.00000	0.02034	0.10000	0.00231	0.02312	0.00000	0.02312
99.000	-4.60517	0.00000	4.41126	26.46734	1.19740	0.04524	0.00000	0.04524
99.000	-4.60517	0.00000	4.41126	26.46734	1.19740	0.04524	0.00000	0.04524
98.000	-3.91202	0.00000	12.43093	67.57704	4.35153	0.06439	0.00000	0.06439
97.000	-3.50656	0.00000	20.28949	86.22609	8.20400	0.09515	0.00000	0.09515
96.000	-3.21888	0.00000	27.33911	93.83186	12.20938	0.13012	0.00000	0.13012
95.000	-2.99573	0.00000	33.53576	97.06260	16.14321	0.16632	0.00000	0.16632
94.000	-2.81341	0.00000	38.96611	98.52015	19.91137	0.20210	0.00000	0.20210
93.000	-2.65926	0.00000	43.73714	99.21694	23.47749	0.23663	0.00000	0.23663
92.000	-2.52573	0.00000	47.94771	99.56766	26.83223	0.26949	0.00000	0.26949
90.000	-2.30259	0.00010	55.01167	99.85349	32.92808	0.32976	0.00000	0.32976
88.000	-2.12026	0.02428	60.67738	99.94436	38.28127	0.38303	0.00024	0.38327
85.000	-1.89712	2.67843	67.30469	99.98466	45.14069	0.45148	0.02679	0.47826
80.000	-1.60944	53.13429	75.08221	99.99754	54.17285	0.54174	0.53136	1.07310
75.000	-1.38629	94.91755	80.35863	99.99948	61.05618	0.61056	0.94918	1.55975
70.000	-1.20397	99.81934	84.12153	99.99987	66.44292	0.66443	0.99819	1.66262
65.000	-1.04982	99.99665	86.90752	99.99996	70.75225	0.70752	0.99997	1.70749
60.000	-0.91629	99.99996	89.03143	99.99999	74.26312	0.74263	1.00000	1.74263
55.000	-0.79851	100.00000	90.68911	100.00000	77.16751	0.77168	1.00000	1.77168
50.000	-0.69315	100.00000	92.00820	100.00000	79.60155	0.79602	1.00000	1.79602
45.000	-0.59784	100.00000	93.07506	100.00000	81.66427	0.81664	1.00000	1.81664
40.000	-0.51083	100.00000	93.94997	100.00000	83.42933	0.83429	1.00000	1.83429
35.000	-0.43078	100.00000	94.67612	100.00000	84.95256	0.84953	1.00000	1.84953
30.000	-0.35667	100.00000	95.28515	100.00000	86.27702	0.86277	1.00000	1.86277
25.000	-0.28768	100.00000	95.80068	100.00000	87.43640	0.87436	1.00000	1.87436
20.000	-0.22314	100.00000	96.24068	100.00000	88.45740	0.88457	1.00000	1.88457
15.000	-0.16252	100.00000	96.61898	100.00000	89.36145	0.89361	1.00000	1.89361
10.000	-0.10536	100.00000	96.94641	100.00000	90.16591	0.90166	1.00000	1.90166
5.000	-0.05129	100.00000	97.23152	100.00000	90.88499	0.90885	1.00000	1.90885
0.000	0.00000	100.00000	97.48114	100.00000	91.53042	0.91530	1.00000	1.91530

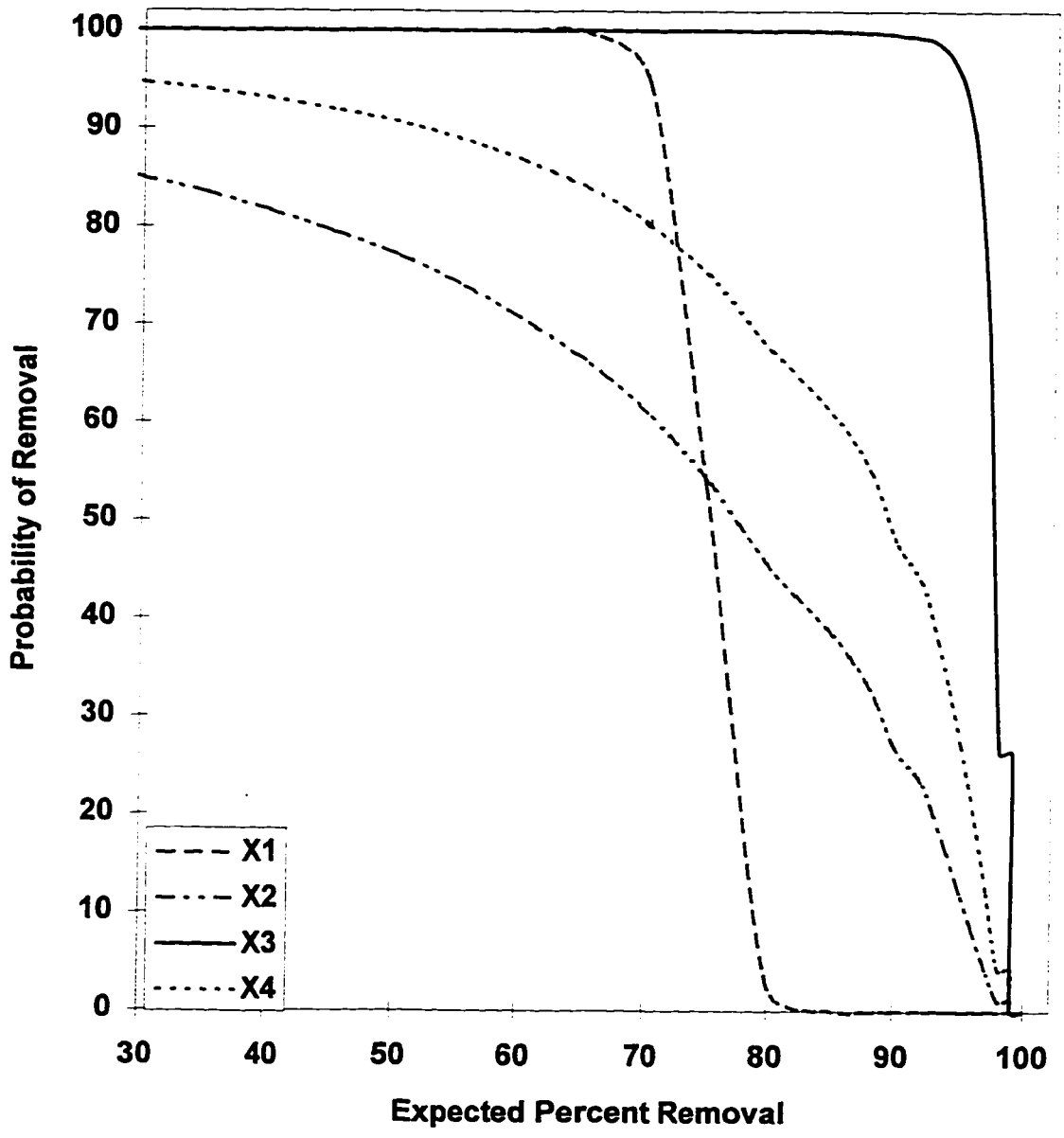


Fig 5.46 : Probability Plot for Removal of *Clostridium perfringens* During Phase II

Table 5.35: Calculations For Factor Of Interaction "λ" (Coliphage: Phase I)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y = 0.7398x - 1.7881	y = 1.1432x - 2.1234	y = 1.2594x - 2.8778	y = 0.4928x - 0.7544	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00004	0.00002	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.04174	0.06874	0.00000	0.00000	0.00000	0.00000
99.000	-4.60517	0.00701	4.15407	8.50969	0.00000	0.00000	0.00082	0.00082
99.000	-4.60517	0.00701	4.15407	8.50969	0.00000	0.00000	0.00082	0.00082
98.000	-3.91202	0.20454	10.58256	20.57653	0.00000	0.00000	0.00994	0.00994
97.000	-3.50656	1.00895	16.70490	30.88009	0.00000	0.00000	0.03267	0.03267
96.000	-3.21888	2.65480	22.21366	39.32632	0.00003	0.00000	0.06751	0.06751
95.000	-2.99573	5.12858	27.12056	46.26969	0.00027	0.00001	0.11084	0.11085
94.000	-2.81341	8.28636	31.49559	52.03879	0.00147	0.00003	0.15923	0.15926
93.000	-2.65926	11.94588	35.41264	56.88814	0.00555	0.00010	0.20999	0.21009
92.000	-2.52573	15.93387	38.93722	61.00904	0.01626	0.00027	0.26116	0.26143
90.000	-2.30259	24.33480	45.02106	67.60700	0.08402	0.00124	0.35994	0.36119
88.000	-2.12026	32.66703	50.08738	72.62485	0.27888	0.00384	0.44981	0.45365
85.000	-1.89712	44.13689	56.27782	78.19184	1.02021	0.01305	0.56447	0.57752
80.000	-1.60944	59.53640	64.01695	84.30605	4.13650	0.04907	0.70619	0.75526
75.000	-1.38629	70.64324	69.66322	88.18525	9.98770	0.11326	0.80108	0.91434
70.000	-1.20397	78.50724	73.95823	90.80870	18.08100	0.19911	0.86453	1.06365
65.000	-1.04982	84.08136	77.32839	92.66751	27.44275	0.29614	0.90734	1.20349
60.000	-0.91629	88.06622	80.03728	94.03235	37.12623	0.39482	0.93655	1.33138
55.000	-0.79851	90.94724	82.25702	95.06326	46.43405	0.48845	0.95670	1.44516
50.000	-0.69315	93.05541	84.10493	95.86011	54.94594	0.57319	0.97074	1.54393
45.000	-0.59784	94.61659	85.66383	96.48798	62.46440	0.64738	0.98060	1.62799
40.000	-0.51083	95.78603	86.99382	96.99083	68.94409	0.71083	0.98758	1.69841
35.000	-0.43078	96.67156	88.13961	97.39921	74.43101	0.76418	0.99253	1.75671
30.000	-0.35667	97.34893	89.13513	97.73494	79.01875	0.80850	0.99605	1.80455
25.000	-0.28768	97.87202	90.00656	98.01391	82.81994	0.84498	0.99855	1.84353
20.000	-0.22314	98.27954	90.77447	98.24791	85.94913	0.87482	1.00032	1.87514
15.000	-0.16252	98.59966	91.45519	98.44587	88.51355	0.89911	1.00156	1.90067
10.000	-0.10536	98.85306	92.06186	98.61461	90.60881	0.91882	1.00242	1.92124
5.000	-0.05129	99.05510	92.60518	98.75944	92.31752	0.93477	1.00299	1.93777
0.000	0.00000	99.21727	93.09390	98.88453	93.70960	0.94767	1.00336	1.95103

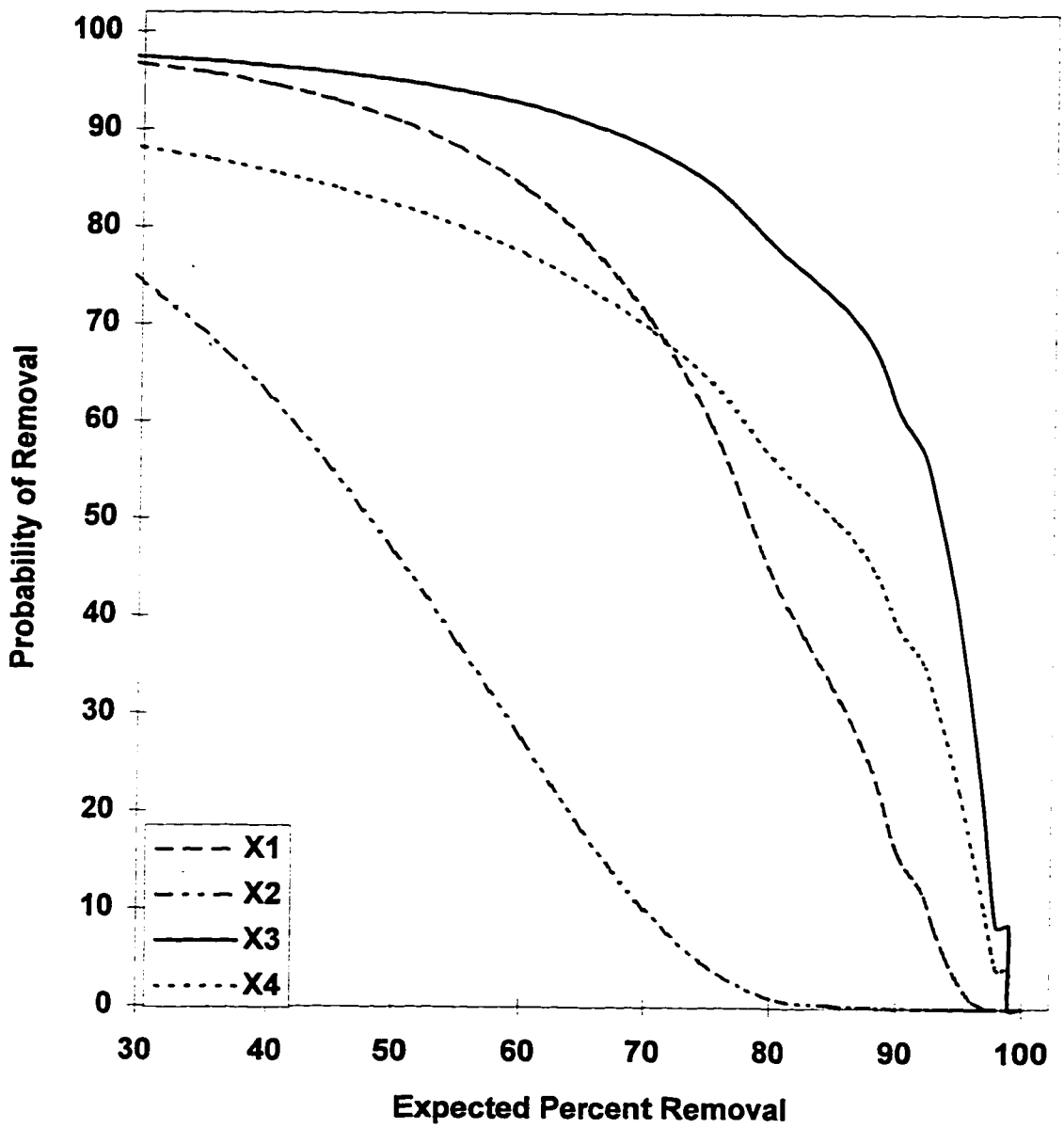


Fig 5.47 : Probability Plot for Removal of Coliphage During Phase I

Table 5.36: Calculations For Factor Of Interaction "λ" (Coliphage : Phase II)

COL#1	COL#2	COL#3	COL#4	COL#5	COL#6	COL#7	COL#8	COL#9
	(CDFs=>)	y = 0.7652x + 1.9683	y = 0.9998x + 4.3492	y = 0.8151x + 5.5933	y = 0.2515x + 1.2441	Chlorination	Filtration	
Rp	ln (C/Co)	P(x1 > Rp)	P(x4 > Rp)	P(x3 > Rp)	P(x2 > Rp)	Effect	Effect	λ
99.990	-9.21034	0.00000	0.00006	0.00046	0.00000	0.00000	0.00000	0.00000
99.900	-6.90776	0.00000	0.52477	5.34124	0.00000	0.00000	0.00000	0.00000
99.000	-4.60517	0.02845	39.89672	88.72974	0.00000	0.00000	0.00032	0.00032
99.000	-4.60517	0.02845	39.89672	88.72974	0.00000	0.00000	0.00032	0.00032
98.000	-3.91202	0.55403	66.90402	98.04278	0.00000	0.00000	0.00565	0.00565
97.000	-3.50656	2.22013	80.03329	99.47680	0.00000	0.00000	0.02232	0.02232
96.000	-3.21888	5.10966	87.08777	99.82103	0.00000	0.00000	0.05119	0.05119
95.000	-2.99573	8.96850	91.20900	99.92807	0.00000	0.00000	0.08975	0.08975
94.000	-2.81341	13.47031	93.77426	99.96757	0.00000	0.00000	0.13475	0.13475
93.000	-2.65926	18.32683	95.45126	99.98406	0.00000	0.00000	0.18330	0.18330
92.000	-2.52573	23.31615	96.59116	99.99162	0.00002	0.00000	0.23318	0.23318
90.000	-2.30259	33.11066	97.96722	99.99729	0.00129	0.00001	0.33112	0.33113
88.000	-2.12026	42.12905	98.71058	99.99898	0.02473	0.00025	0.42129	0.42154
85.000	-1.89712	53.70568	99.29080	99.99971	0.47090	0.00471	0.53706	0.54177
80.000	-1.60944	68.04574	99.69309	99.99995	7.31625	0.07316	0.68046	0.75362
75.000	-1.38629	77.65499	99.84791	99.99999	28.59059	0.28591	0.77655	1.06246
70.000	-1.20397	84.10686	99.91719	100.00000	56.33828	0.56338	0.84107	1.40445
65.000	-1.04982	88.49906	99.95166	100.00000	78.00840	0.78008	0.88499	1.66507
60.000	-0.91629	91.54057	99.97021	100.00000	90.37836	0.90378	0.91541	1.81919
55.000	-0.79851	93.68356	99.98084	100.00000	96.17811	0.96178	0.93684	1.89862
50.000	-0.69315	95.21862	99.98723	100.00000	98.57621	0.98576	0.95219	1.93795
45.000	-0.59784	96.33523	99.99123	100.00000	99.49097	0.99491	0.96335	1.95826
40.000	-0.51083	97.15904	99.99382	100.00000	99.82249	0.99822	0.97159	1.96982
35.000	-0.43078	97.77475	99.99556	100.00000	99.93893	0.99939	0.97775	1.97714
30.000	-0.35667	98.24043	99.99674	100.00000	99.97910	0.99979	0.98240	1.98220
25.000	-0.28768	98.59652	99.99757	100.00000	99.99285	0.99993	0.98597	1.98589
20.000	-0.22314	98.87156	99.99816	100.00000	99.99754	0.99998	0.98872	1.98869
15.000	-0.16252	99.08596	99.99859	100.00000	99.99915	0.99999	0.99086	1.99085
10.000	-0.10536	99.25454	99.99890	100.00000	99.99970	1.00000	0.99255	1.99254
5.000	-0.05129	99.38815	99.99914	100.00000	99.99989	1.00000	0.99388	1.99388
0.000	0.00000	99.49482	99.99932	100.00000	99.99996	1.00000	0.99495	1.99495

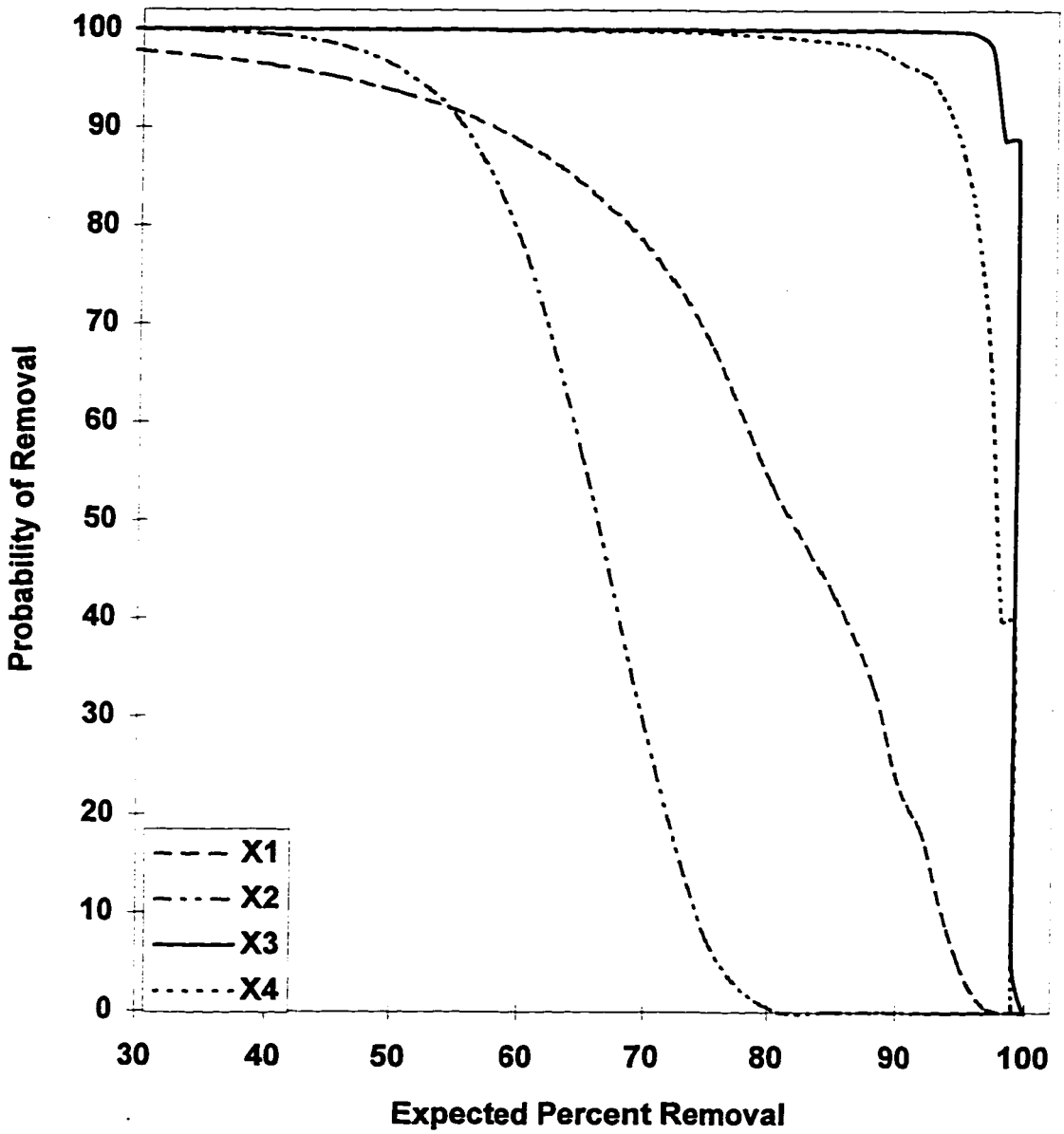


Fig 5.48 : Probability Plot for Removal of Coliphage During Phase II

Where

λ = Interaction factor

R_p = Safe removal level

x2 = Probability that the safe removal level, R_p, will be achieved by chlorination alone

x1 = Probability that the safe removal level, R_p, will be achieved by slow sand filtration alone (control filter)

x3 = Probability that the safe removal level, R_p, will be achieved by the combination of chlorination and slow sand filtration.

Table 5.25 gives a typical spreadsheet solution for finding the interaction factor λ. COL#1 represents the expected removals Rp which are to be achieved by either a single treatment like chlorination alone or control filtration or a combination of treatments as expected in the test filtration. The corresponding ln(C/C0) for the Rp are given in COL#2. COL#3 gives the probability of the expected removals and is termed as x1. This is obtained by substituting the values in COL#2 and the EXCEL function NORMSDIST in the CDF's obtained in Step 1. Therefore the probability that the control filter will achieve the desired removals Rp is termed as x1 and shown in COL#3. Similarly COL#4, and 5 represent the probability that either chlorination alone or test filtration will achieve the desired removals. These have been termed as x2 and x3 respectively. The effect of chlorination is obtained from the ratio of

COL#4 and COL#5. This represents the contribution of chlorination towards the overall removal in the test filtration and is obtained as a ratio of x2 and x3. The effect of filtration is calculated as the ratio of COL#3 and COL#5, and represents the contribution of slow sand filtration towards the overall removals obtained in the test filtration. This is obtained as the ratio of x1 and x3 To check for additivity both the chlorination and filtration effects are summed up. Therefore the sum of COL#7 and COL#8 represents the interaction factor λ as given in the COL#9. The interaction factor is found over a range of Rp. The factor of inactivation is then plotted against the expected safe levels. Similarly Tables 5.25 to 5.36 gives the calculations for the different indicator microorganisms. Figure 5.49 is the plot of Rp (COL#1) vs. λ (COL#9). Figures 5.49 to 5.54 give the plots of the interaction factor against the desired safe levels Rp for the different indicators microorganisms.

The microbial removals of the control filter compared to the test filter show that the test filter outperformed the control filter on all counts in both the phases. This is interpreted as due to the combined effect of chlorination and filtration. The loss of *schmutzedecke*, if any, did not interfere with the removals in the test filter. The variations in removal efficiencies were also greatly reduced giving a consistent removal within a very narrow range. In order to determine the extent of interaction the modified Berenbaums equation was used.

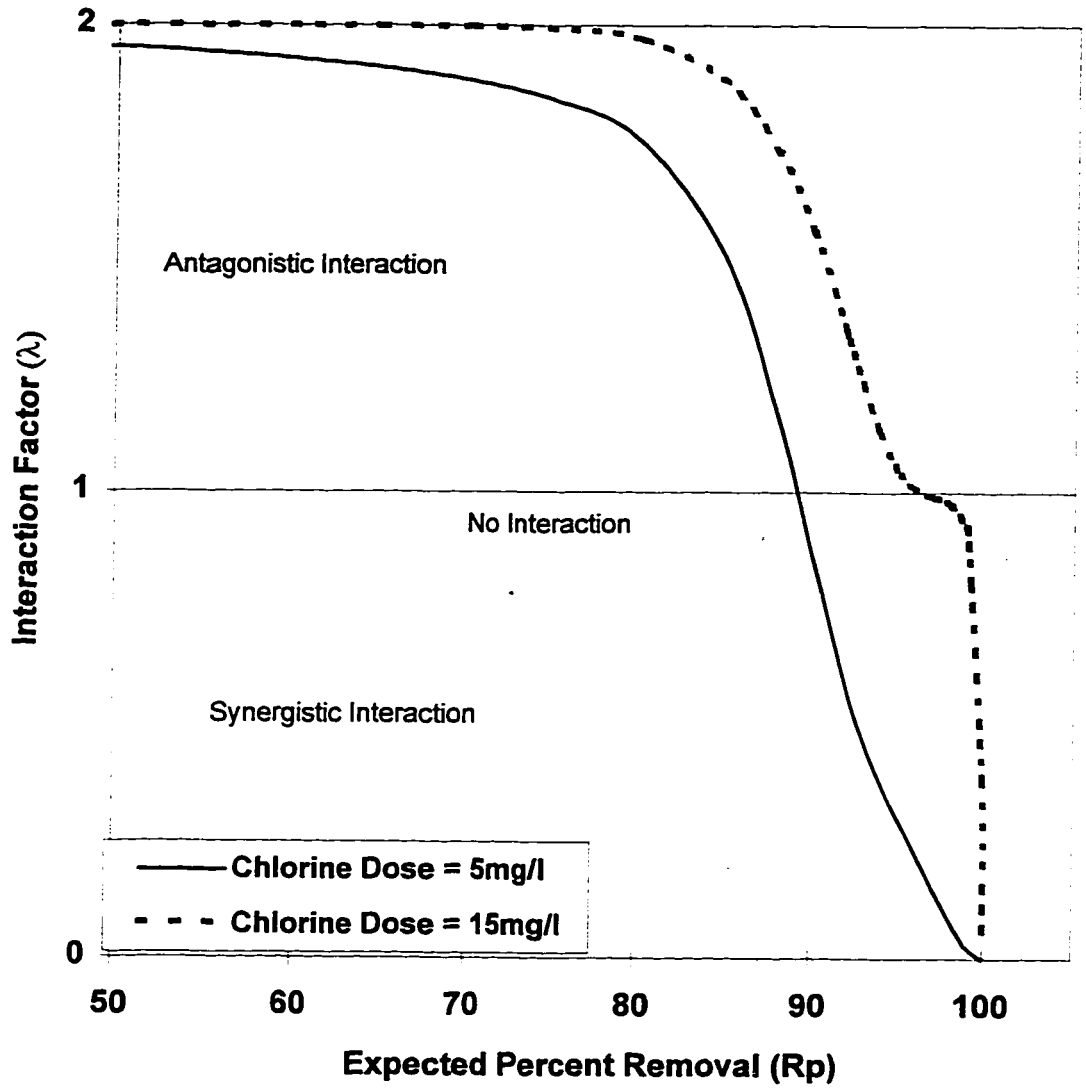


Fig 5.49 : Effect of Chlorine Dose on the Removal of Standard Plate Count During Slow Sand Filtration

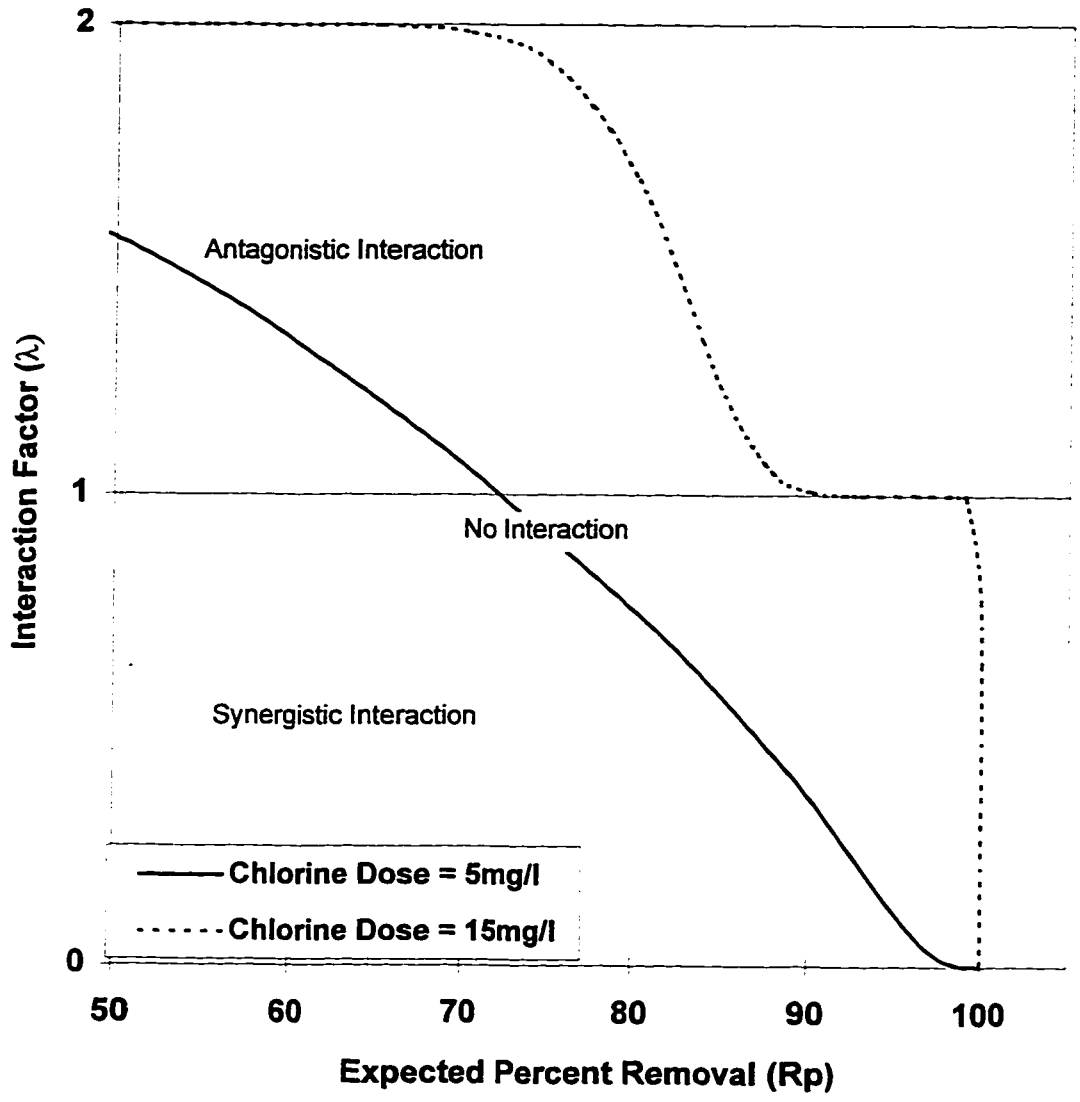


Fig 5.50 : Effect of Chlorine Dose on the Removal of Total Coliform During Slow Sand Filtration

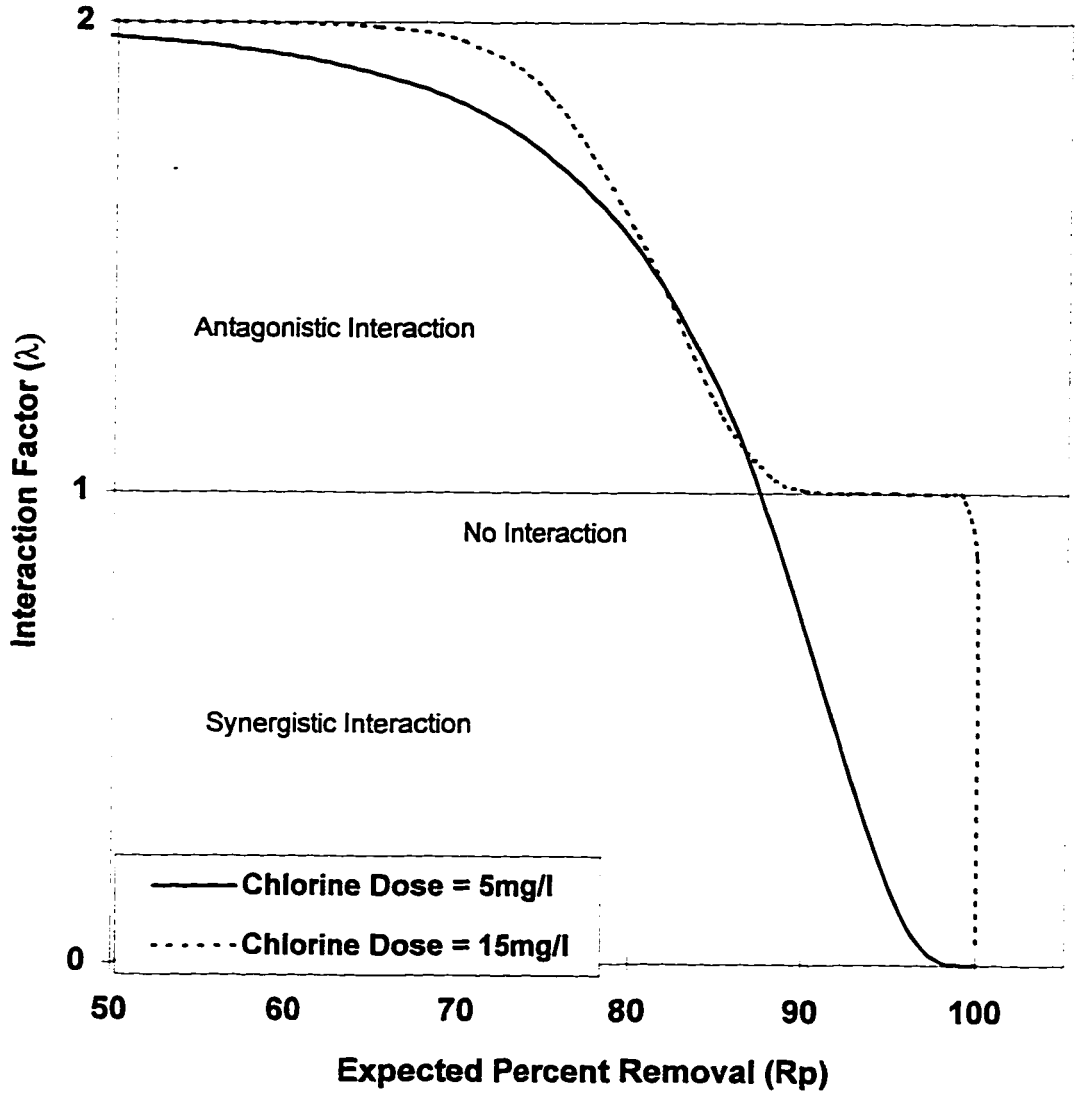


Fig 5.51 : Effect of Chlorine Dose on the Removal of Fecal Coliform During Slow Sand Filtration

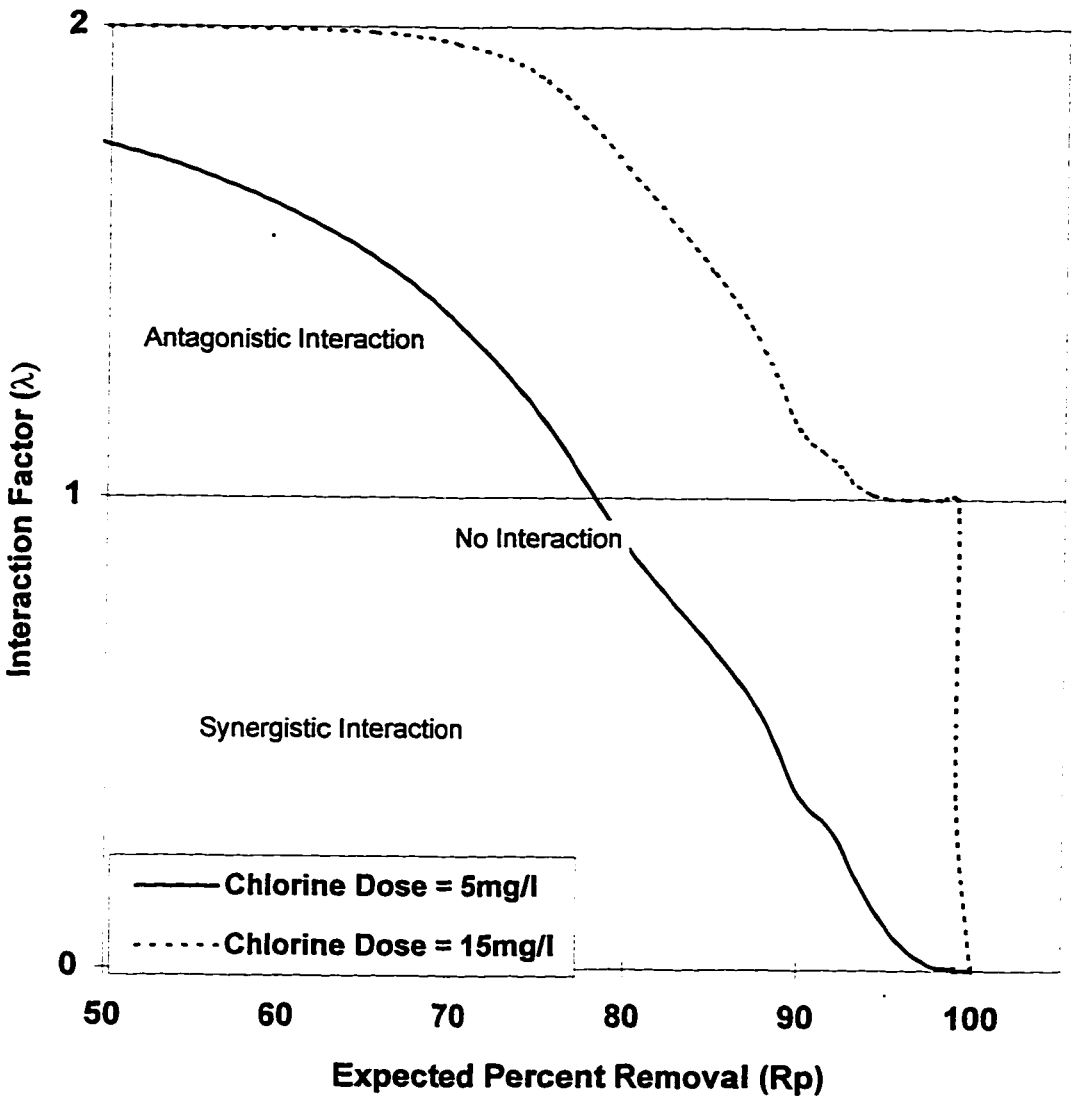


Fig 5.52 : Effect of Chlorine Dose on the Removal of Fecal Streptococcus During Slow Sand Filtration

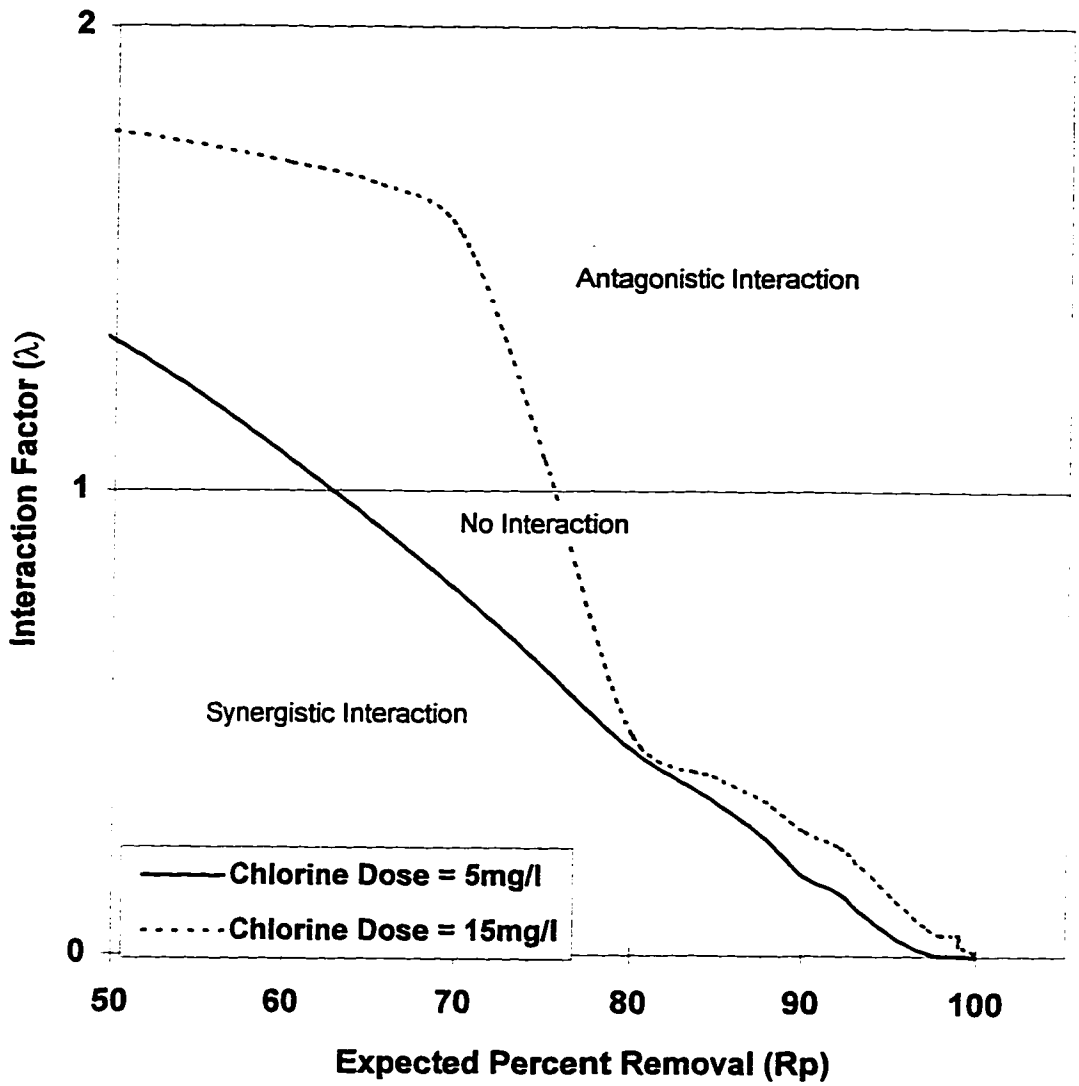


Fig 5.53 : Effect of Chlorine Dose on the Removal of Clostridium perfringens During Slow Sand Filtration

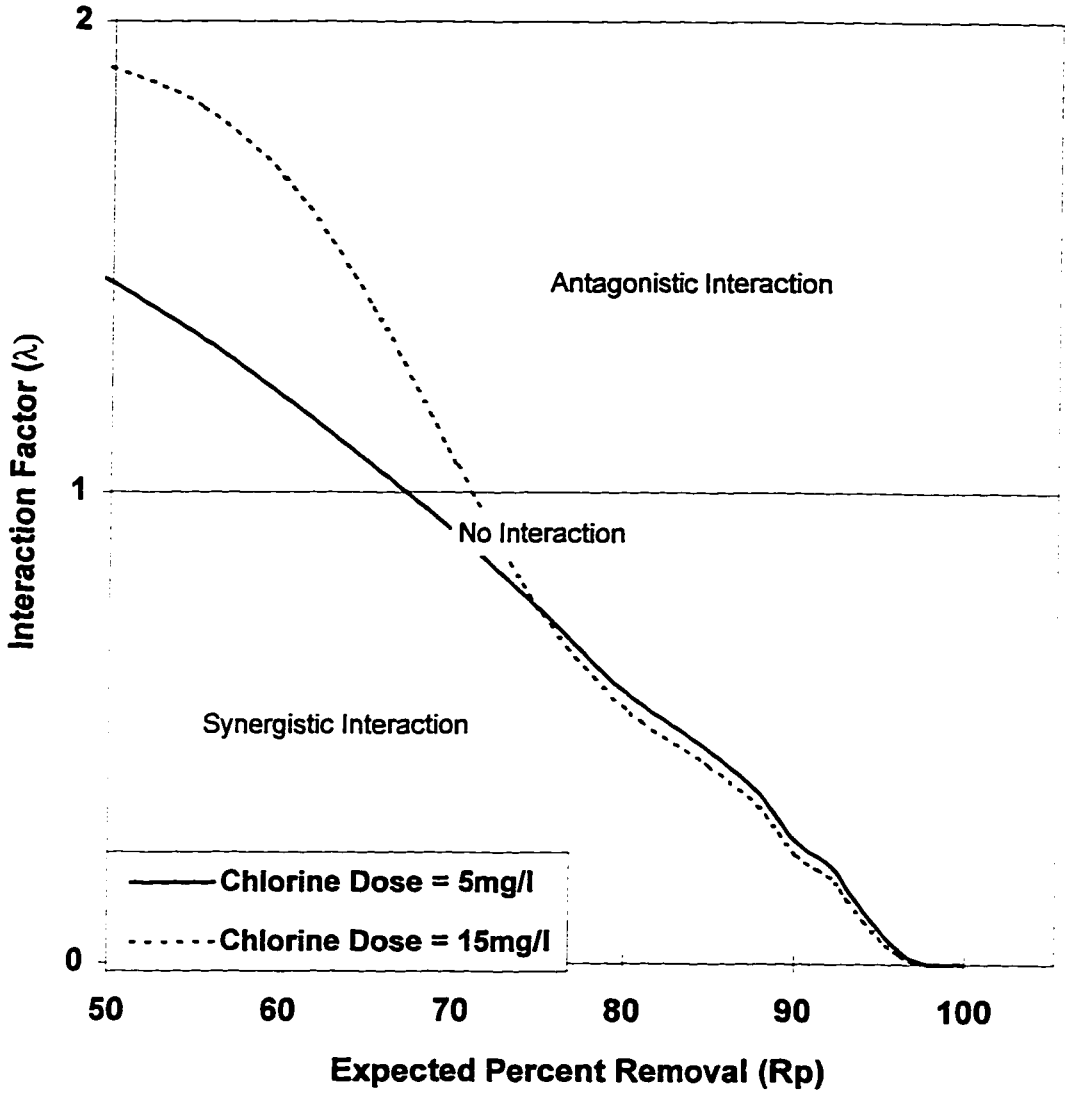


Fig 5.54 : Effect of Chlorine Dose on the Removal of Coliphage During Slow Sand Filtration

It is observed that the factor of interaction approaches synergy at greater desired removals, R_p, and at lower values of R_p it approaches 2. This is due to the fact prechlorination is essential for slow sand filters to achieve larger values of R_p. As the value of R_p is decreased, the slow sand filter does not require chlorination to achieve R_p, as it is capable of doing so on its own account. Thus it can be inferred that chlorination is essential only when a greater quality of effluents is required. The theoretical R_p at which the value of the interaction factor approaches 1, can be achieved by slow sand filtration alone without the aid of chlorination. As the value of R_p decreases the interaction factor approaches the zone of antagonism. In this zone the removals due to slow sand filter and chlorination are not complementary as either of the two processes can achieve the required R_p without the help of the other. The plots of R_p vs. the interaction factor for different microorganisms is given in Figs. 5.49 - 5.54.

Theoretically speaking the point of zero interaction should be the same for both the chlorine doses. But as observed from the plots, there is a distinct difference in the R_p values at an interaction factor of 1. The higher values of R_p for the second phase can be interpreted as the effect of a chlorine residual throughout the length of the filter. This gives an apparent increased removal in the test filter. The only exception to this observation is fecal coliform.

5.5 Interpretation of the Interaction Curves

The interaction curves give the type of interaction, i.e., synergistic, antagonistic or additive, that can be expected at different safe levels.

For instance from Fig 5.54, it is observed that for an expected safe coliphage removal of about 80% the curve lies in the synergistic interaction curve. This implies that chlorination is essential if a 80% coliphage removal is required, as slow sand filter alone is incapable of achieving this level of removal. Further at an expected removal of about 67%, the interaction curve touches the no interaction line. This means that slow sand filter alone is capable of dealing with this level of removals and does not require chlorination at all. For expected removals less than 67%, the interaction curve lies in the antagonistic region. This implies that slow sand filters are capable of removing coliphage in this level without any assistance from chlorination and chlorination if done, is purely additive in nature. This does not mean that if prechlorination is practiced in this zone, it will effect no removal. In fact it does have its removal, but this removal is purely extraneous and does not help the slow sand filter in any way.

The ideal interpretation of these interaction curves would be in determining what level of removal is required and if that removal is achievable by slow sand filtration alone. In case slow sand filters cannot provide that level

of removals, it is then evaluated whether prechlorination can help in achieving it.

Since two extreme dosages of chlorination have been chosen in this study, it is possible to predict the maximum removals that can be achieved by prechlorinating of filter influents.

The shape of the curve in the 5 mg/l, as seen in Figs 5.49-5.54, is smooth in all the indicator removals. This indicates that the dose is appropriate for an efficient microbial removal. The curves for the 15 mg/l chlorine dose show a sharp flat at the '$\lambda = 1$' line. This is due to the great difference in the chlorination and slow sand filtration efficiencies. A flat indicates that the removals at that point are due to only one of the agent (in this case chlorine).

An interesting observation was made in the removals of chlorine resistant indicators, *Cl. perfringens* and coliphages. The interaction lines followed the same pattern and were almost interlinked. This indicates that the higher doses of chlorine have no significant effect on the performance of the slow sand filter with regards to removal of *Cl. perfringens* and coliphages. The behavior of *Cl. perfringens* can be because the maximum removals were obtained at lower chlorine dosage and the remaining population formed resistant cysts that were more resistant to chlorination.

Kott *et al.* have reported that the coliphage group consisted of chlorine resistant strains that were not inactivated with 80 mg/l chlorine dose. The

observations made here could be due to the fact that the resistant strains of coliphage were present in both the phases.

5.6 Development of Headloss and Filter Run

The rate of headloss development in the test filter was far slower than that in the control filter at all times. A filter run greater than 53 days was observed without the terminal headloss being reached under both the phases.

Table: 5.37: Headloss in Control and Test Filters

Filter	Headloss After 53 Days of Operation
Control Filter	59.0 in
Test Filter (Chlorine Dose = 5 mg/l)	28.5 in
Test Filter (Chlorine Dose = 15 mg/l)	8.6 in

The controlling effect of oxidants on the headloss is well documented in literature [Ellis, 1985; LeChevallier *et.al.* 1992; Goldgrabe *et.al.*,1993; Farooq and Imran, 1997a,1997b]. This was evident in the fact that though the control filter reached terminal headloss two times during the period of the study, the test filter had yet to reach terminal headloss.

The reduced rate of headloss did not interfere in any way with the removal efficiencies of various microorganisms during the run. This can be seen in the enhanced removals in the test filter. The headloss development

with time for the control filter can be seen in Fig 5.55. This reduced rate of headloss is bound to be reflected in the longer filter runs, thereby reducing the downtimes required for filter cleaning.

The headloss development in the test filters was progressive rather than exponential. Greaves *et.al.*,[1988], reported similar observations in their pilot plant studies involving the removal of color in preozonated influents.

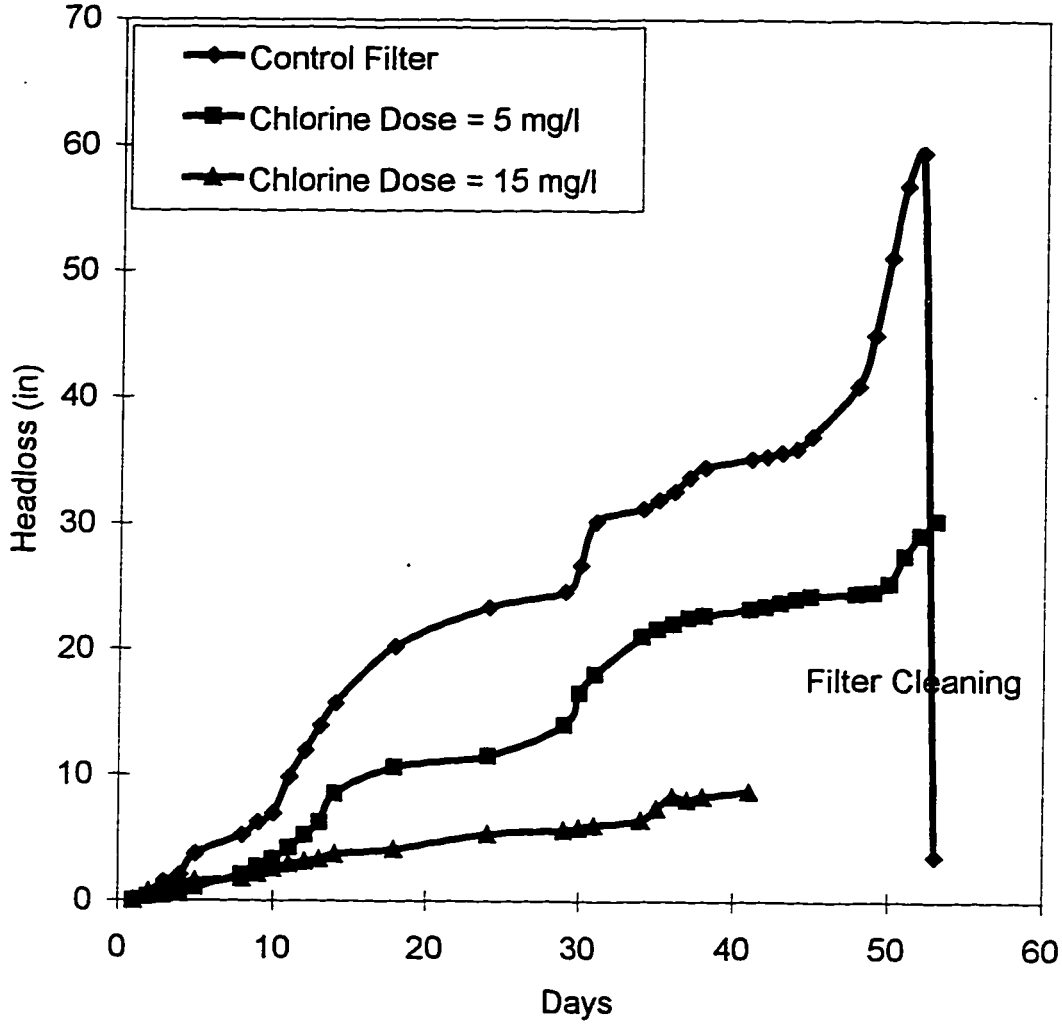


Fig 5.55 : Headloss Variation in Control and Test Filters under Phase I and Phase II

CHAPTER # 6

6. SUMMARY AND CONCLUSIONS

6.1 Summary

The objectives of this study were to investigate and monitor the removal of bacterial and viral indicator microorganisms through slow sand filters under two different prechlorination doses, of 5 and 15 mg/l, on a pilot plant under field conditions. One slow sand filter was utilized to treat settled secondary effluent from the Al-Khobar Sewage Treatment Plant. This acted as control filter to enable comparisons to be made. The second filter, called as test filter, was utilized to treat the chlorinated settled secondary effluent. The chlorination chamber was incorporated from which the chlorinated settled secondary effluent was supplied to the test filter. In order to maintain identical conditions the sand size, depth of sand media, and flow rate were kept the same in order to facilitate comparisons. The flow rate was maintained at 10

l/min, throughout the period of the study, in both the filters. The sand size was 0.5 mm with a depth of sand media at 1.0 m. To get a clearer picture of the microbial removals due to the different treatment levels namely, chlorination, control slow sand filtration and test filtration that incorporates the combined effects of chlorination and subsequent filtration were studied. Six different microbial parameters were selected because they are widely recommended as indicators of pathogens in waters and wastewater. These are standard plate count, total coliform, fecal coliform, fecal streptococcus, *Clostridium perfringens* and coliphage. The study was conducted in two phases. In Phase I the chlorine dose was kept at 5 mg/l. Phase II which commenced 2 weeks after completion of Phase I utilized a chlorine dose of 15 mg/l. The results of these two phases are summarized as follows,

- During Phase I, standard plate counts in the settled secondary effluent had an average around 1.7×10^4/ml. And the corresponding removals were 87.8%, 87.3% and 98.6% for the control filtration, chlorination and test filtration respectively.
- During Phase II, standard plate counts in the settled secondary averaged around 2.55×10^4 /ml. And the corresponding removals were 89.9%, 99.74% and 99.96% for the control filtration, chlorination and test filtration respectively.
- The total coliforms in the settled secondary effluent, during Phase I, averaged at 3.47×10^5 MPN/100ml. And the corresponding removals

were 83.4%, 76.6% and 98.2% for the control filtration, chlorination and test filtration respectively.

- During Phase II, the total coliforms in the settled secondary effluent averaged at $1.17x10^5$ MPN/100ml. The corresponding removals for the control filtration, chlorination and test filtration were 81.68%, 99.93% and 99.994% respectively.

- During Phase I, the fecal coliform in the settled secondary effluent averaged at $1.85x10^5$ MPN/100ml. And the corresponding removals were 81.7%, 84.9% and 98.1% for the control filtration, chlorination and test filtration respectively.

- During Phase II, the fecal coliform in the settled secondary effluent ranged averaged at $8.96x10^4$ MPN/100ml. The corresponding removals in control filtration, chlorination and test filtration were 86.44%, 99.95% and 99.995% respectively.

- The fecal streptococcus in the settled secondary effluent, during Phase I, averaged at $1.56x10^4$ MPN/100ml. And the corresponding removals were 82.3%, 72.6% and 97.5% for the control filtration, chlorination and test filtration respectively.

- During the Phase II, the fecal streptococcus in the settled secondary effluent ranged averaged at $7.55x10^3$ MPN/100ml. The corresponding

removals in control filtration, chlorination and test filtration were 87.1%, 99.81% and 99.998% respectively.

- The *Clostridium perfringens* in the settled secondary effluent, during Phase I, averaged at $1.24x10^2$ /100ml. And the corresponding removals were 79.0%, 44.5% and 89.5% for the control filtration, chlorination and test filtration respectively.
- During Phase II the *Clostridium perfringens* in the settled secondary effluent averaged at $2.85x10^2$ /100ml. The corresponding removals in control filtration, chlorination and slow sand filtration were 80%, 71.35% and 92.3% respectively.
- The coliphage count in the settled secondary effluent, during Phase I averaged at $7.7x10^2$ PFU/100ml. And the corresponding removals were 80.1%, 49.1% and 91.3% for the control filtration, chlorination and test filtration respectively.
- During Phase II, the coliphage count in the settled secondary effluent averaged at $9.92x10^2$ PFU/100ml. The corresponding removals in control filtration, chlorination and test filtration were 82.7%, 70.6% and 99.55% respectively.
- The headloss at the end of 53 days operation was 59.0, 28.5 and 8.6 inches for the control filter, and test filter with a prechlorination dose of 5 and 15 mg/l respectively.

6.2 Conclusions

Based on the results of this study the following specific conclusions can be drawn:

1) Coliphages and *Clostridium perfringens* were more resistant to chlorination than all the other indicator organisms studied. The coliform bacteria were present even in the effluent from the test filters under a high chlorine dose. This establishes the effectiveness of the coliform indicators. Thus they can be used as microbial indicators in studies involving chlorination efficiency.

2) The overall removals of indicator microorganisms in both the phases of the study was far better than either the control filter or chlorination alone. This establishes the need for prechlorination of slow sand filters.

3) The higher chlorine doses, as established by the interaction model, could not utilize the inherent filtration capacity of the slow sand filters efficiently for microbial removals. Therefore higher chlorinating dosages prove to be uneconomical. The best solution would be to prechlorinate at a lower chlorine dose.

4) The headloss in the prechlorinated filter was greatly reduced resulting in considerably longer run times. The headloss at the end of 53 days operation was 59.0, 28.5 and 8.6 inches for the control filter, and test filter with a prechlorination dose of 5 and 15 mg/l respectively. This is

expected to have a significant impact on the economy of filter operations.

CHAPTER # 7

7. RECOMMENDATIONS

Based on the experiences and observations made during this study the following specific recommendations have been made to for future research work.

1) A field study on the indicator to pathogen ratio in wastewaters need to be made in the Kingdom of Saudi Arabia, so as to correlate the work done on the indicator microorganisms to the actual risk of microbial infection.

2) Studies on the formation potential of disinfection by-products in wastewaters is an urgent need if reclaimed wastewater is to be considered for reuse. This will help in establishing the carcinogenic potential of disinfected wastewaters.

3) Chlorination of secondary effluents prior to sand filtration is to be considered at all design levels, because of their obvious advantages.

4) A logical extension of this study would be to study the removal of disinfection byproduct precursors in the wastewaters by slow sand filtration. This will help in evaluating whether chlorination of wastewaters is resulting in the production of any harmful disinfection byproducts.

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