I

UNITED STATES ATOMIC ENERGY COMMISSION

NYO-4990

AN EVALUATION OF LAUNDERING AGENTS
AND TECHNIQUES USED IN THE DECONTAMINATION
OF COTTON CLOTHING

By
Albert P. Talboys
Eugene C. Spratt

March 1, 1954

The Johns Hopkins University
Baltimore, Maryland

Technical Information Service, Oak Ridge, Tennessee

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Subject Category, CHEMISTRY.

Issuance of this document does not constitute authority for declassification of classified material of the same or similar content and title by the same authors.

This report has been reproduced with minimum alteration directly from manuscript provided the Technical Information Service in an effort to expedite availability of the information contained herein.

Reproduction of this information is encouraged by the United States Atomic Energy Commission. Arrangements for your republication of this document in whole or in part should be made with the author and the organization he represents.

Printed in USA, Price 80 cents. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

AN EVALUATION OF LAUNDERING AGENTS AND TECHNIQUES
USED IN THE DECONTAMINATION OF COTTON CLOTHING

Report JHUL-4

by

Albert P. Talboys
Eugene C. Spratt

March 1, 1954

Department of Sanitary Engineering
and Water Resources
The Johns Hopkins University
Baltimore, Maryland

Contract No. AT(30-1)-1947

AN EVALUATION OF LAUNDERING AGENTS AND TECHNIQUES
USED IN THE DECONTAMINATION OF COTTON CLOTHING

Table of Contents

	<u>Page</u>
I. Introduction	1
II. Materials and Methods	4
III. Tests of Actual Laundry Procedures	10
IV. Decontaminating Efficiency of Various Detergents and Sequestering Agents	20
V. Importance of Contaminating Conditions	36
VI. Effects of Variation in Laundering Technique	50
VII. Effects of Laundering Aids and Pre-Treatment of Cloth	71
VIII. Investigation of Dry Cleaning Techniques	83
IX. Summary	93
X. Appendix	101

I. INTRODUCTION

100-4770

In its overall aspects, the removal of radioactive contaminants from protective clothing worn by workers engaged in various phases of the atomic energy program has been a costly undertaking. This is true not only because the clothing is laundered and monitored, but also because the radioactive wastes resulting from the laundering operations have to be disposed of in a safe manner. While these wastes are generally of a low level of radioactivity, the nature and concentration of some decontaminating agents which have been used make them difficult to treat, either chemically or biologically. At installations where it is necessary to concentrate and store the wastes, the considerable volumes of waste produced by multiple washing and rinsing procedures have resulted in high evaporation costs.

This study was undertaken to attack the waste disposal problem at its source, in the laundry itself, rather than trying to further improve and adapt various existing treatment and concentration processes. Our attention was therefore directed primarily toward:

- (1) An evaluation of laundering agents used in the decontamination of clothing, with a view to employment in the laundry of agents which are effective decontaminants and still amenable to treatment by economical biological processes;

- (2) A determination of techniques, including "dry cleaning" methods, affording maximum decontaminating efficiency and at the same time resulting in a minimum volume of waste to be evaporated.

The radioactive contaminants used in the tests, strontium 89, yttrium 91, cerium 141, iron 59, phosphorus 32, and iodine 131, cover a wide range of characteristics with regard to chemical behavior and potential health hazard. They include isotopes widely used in research and therapy as well as fission products commonly encountered at the atomic energy installations. The isotopes were studied individually rather than as mixtures in order that the effects of the different agents and techniques would be more clearly delineated. Since almost all of the uniforms, coveralls, laboratory coats, and hospital bedding used up to the present in connection with radioactivity work and subjected to laundering are made of cotton in various weaves and finishes, the study was limited to the removal of contaminants from cotton cloth.

Representative complexing agents, detergents, and mixtures were tested for decontaminating efficiency to find out how specific the various agents are in their action on different isotopes and to what extent substitution of agents might be practicable in the elimination of waste treatment difficulties. The influence of wash bath temperature, strength of solution, loading of the wash-wheel, and duration of washing on decontaminating efficiency were studied. Tests

were also conducted to see if particulate matter is removed more or less readily than water-soluble or precipitated contaminants, and to note the effects of level of contamination, previous laundering, soiling, starching, and wet-proofing of material by silicone treatment on ease of decontamination. In addition, the use of non-aqueous "dry cleaning" type solvents in the bulk phase of the wash bath as carriers for small volumes of immiscible aqueous decontaminating solutions was investigated.

Information is available on the removal of uranium compounds from cotton cloth as a result of work done at the University of Rochester in 1950.^{1/} In addition, a report was issued by the Army Quartermaster Corps in 1951^{2/} describing the results of field tests on removal of contamination picked up by personnel moving about in areas contaminated by fall-out from atomic weapons bursts. Both of these studies are referred to in subsequent sections of this report, and laundering procedures worked out by various governmental agencies were tested here on a laboratory scale to determine their relative effectiveness in removing contaminants from cloth.

^{1/} Carlson, A.B., and Neuman, W.F., "The Removal of Uranium Compounds from Cloth", AEC Publication UR-108, June 19, 1950.

^{2/} Steadman, Col. F.M., and Staff, "Protective Clothing and Decontamination", Summary Report, Project 6.9, Office of the Quartermaster General, Washington 25, D.C., June 9, 1951.

II. MATERIALS AND METHODS

The laundering tests were carried out by separately contaminating small circular samples of cotton cloth with Sr^{89} , Y^{91} , Ce^{141} , Fe^{59} , P^{32} , and I^{131} , counting the samples, subjecting them to a series of washing and rinsing operations, and re-counting them.

The cloth samples used in the tests were obtained by cutting up soiled, discarded laboratory coats. These white coats, made of light cotton duck, had been used in the Sanitary Engineering Radiological Laboratory at The Johns Hopkins University. The circular pieces were approximately nine square inches in area and weighed 1.58 grams on the average. Practically all of the samples were used "as is", in a slightly soiled condition, and on the whole were quite iniform in appearance. If excessively soiled material was used, it was laundered and thoroughly rinsed before the pieces were contaminated for the decontamination tests.

Contamination was accomplished by immersing the samples for 15 to 30 minutes in solutions of various isotopes. The chemical forms of the isotopes used were as follows:

Sr^{89} : $\text{Sr}(\text{NO}_3)_2$, highly diluted isotopically

Y^{91} : YCl_3 , carrier-free

Ce^{141} : CeCl_3 , carrier-free

Fe^{59} : FeCl_3 , slightly diluted isotopically

P^{32} : H_3PO_4 , isotopically diluted

I^{131} : NaI , carrier-free

In some tests with Sr^{89} and Fe^{59} , compounds of the isotopes were precipitated on the cloths. In other tests, dry, finely divided inert material carrying the same two isotopes was dusted onto the samples and then "ground" into the fabric with a hard rubber roller. This latter operation was carried out in a rubber gloved "dry box". The level of contamination attained in nearly all cases was of the order of several thousand counts per minute per sample.

The laundering operations were performed in 500 ml. Florence flasks attached to Burrell wrist-action shakers, as shown in Figure 1. Satisfactory agitation was obtained by using 50 ml. of solution per sample and one sample per flask. In tests involving two cloths per flask, 100 ml. volumes were used. Except when actual laundry procedures were used, the laundry cycle generally followed consisted of a 10-minute wash, a 5-minute water rinse, another 10-minute wash with fresh solution, and a final 5-minute rinse. In order to simplify the laboratory procedure, solutions were used at room temperature (72-75°F.) A separate series of tests was run, however, to ascertain the importance of using hot solutions. For these tests, Pyrex immersion heaters regulated by Powerstats were inserted into the flasks to maintain the solutions at the desired temperature levels.

After each individual laundering operation the cloths were removed from the flasks, dried, counted on both sides to determine

Figure 1

Wrist-action shaker with
Florence flasks attached

Figure 2

View of apparatus used for drying
cloths, showing infra-red lamps and fan

the removal accomplished, and returned to the flasks for the subsequent operation. (Results of special tests run to compare overall removals obtained by this procedure with those obtained by drying and counting only after the final operation are presented in the Appendix in Table A-1). Excess liquid was removed from the samples before they were dried by pressing the cloths by hand between two heavy watch glasses. Drying was accomplished at temperatures of 105-115° F. by suspending the samples under infra-red lamps in a current of moving air, as shown in Figure 2.

The counting set-up is shown in Figure 3. The dried cloth samples were placed on a wire cloth support surrounding a mica end-window G-M counter, and were held flat by means of a lead disc

Figure 3

View of apparatus
used for holding the
cloths while making
activity counts.

to keep the counting geometry constant. The G-M tube was positioned so that the window was $\frac{1}{4}$ -inch from the cloth sample being counted. A thin sheet of Parafilm was taped in place on the wire cloth to keep radioactive particles from dropping onto the tube window, and was wiped off between counts.

Decontaminating agents used in the laundering tests

included:

- (1) Ammonium citrate - a complexing agent
- (2) Calgon - an inorganic complexing agent
- (3) Citric acid - an acidic complexing agent
- (4) CP Cleaner - a general purpose decontaminating agent
- (5) Demineralized water
- (6) Du Rite (Formula 85) - an inexpensive anionic detergent
- (7) Igepal CO - a non-ionic detergent
- (8) Nacconol NR - a high quality anionic detergent (synthetic)
- (9) Radiacwash - a general purpose decontaminating agent
- (10) Rinso - an anionic detergent (soap)
- (11) Roccal - a cationic sanitizing agent
- (12) Sodium bicarbonate
- (13) Sodium citrate - an alkaline complexing agent
- (14) Tap water
- (15) Versene (Regular) - a chelating agent

While many other chemicals, detergents, and mixtures could have been utilized in the tests, the various agents listed above are representative of most types already proved to be effective in laundering, cleaning, and/or decontamination applications. All solutions were made up with demineralized water, except where specifically noted. Concentrations ranged from 0.3 to 6.0 per cent, calculated on a weight basis in the case of solid substances and on a volume basis in the case of liquids.

In the "dry cleaning" tests, the same general procedure was followed as in the laundering tests, except that the major portion (in most cases 90 per cent) of the wash bath consisted of an organic solvent immiscible with water, such as Stoddard solvent. Various decontaminating agents were usually present in the aqueous phase in one per cent concentrations.

All tests throughout the study were conducted in duplicate, and repeated in many instances for verification of results. Inherent variability of the data obtained is indicated by the statistically analysed results of special runs made with a large number of samples, presented in the Appendix in Table A-2.

III. TESTS OF ACTUAL LAUNDRY PROCEDURES

A series of test runs was made first of all to check the effectiveness of several actual laundering procedures in removing water-soluble radioactive contaminants from cotton cloth. To provide a basis for evaluating the different procedures, a number of multiple rinsing tests were also conducted using water alone as the decontaminating agent.

Commercial Laundry Procedure

The initial runs were made according to an ordinary commercial laundry procedure, as described by Gehm.^{3/} The operations included were a "break" with washing soda, two successive soapings, three hot water rinses, and a citric acid "sour". A final rinse was added in the tests performed here. One per cent Rinso solutions were used for the suds, and three per cent citric acid for the sour, somewhat higher concentrations than would be used commercially.

Results of runs made with Sr^{89} , P^{32} , and I^{131} contaminated cloths are given in Table 1, along with the solution temperatures used. I^{131} was easily removed by this procedure. However, neither Sr^{89} nor P^{32} were completely removed. The initial alkaline "break" was particularly ineffective in removing the latter two isotopes,

^{3/} Gehm, H. W., "Volume Characteristics and Disposal of Laundry Wastes," Sewage Works Journal, Vol. 16, No. 3, May 1944, p 575.

Table 1

REMOVAL OF RADIOACTIVE CONTAMINANTS FROM
COTTON CLOTH BY A COMMERCIAL LAUNDRY PROCEDURE*

Test Conditions:

Duration of each wash and rinse: 5 minutes

Tap water used in all solutions and rinses

Level of contamination: Sr^{89} : 4700-5400 c/m/sample

P^{32} : 2600

I^{131} : 1400-2200

	<u>Commercial Laundry Procedure</u>	<u>Temp. of Solution</u>	<u>Cumulative Percent Removal</u>		
			<u>Sr^{89}</u>	<u>P^{32}</u>	<u>I^{131}</u>
(1)	Break - 1% Na_2CO_3	110° F	25.2	26.9	86.7
(2)	Suds - 1% Rinso	110°	60.8	65.3	97.8
(3)	Suds - 1% Rinso	110°	74.6	88.4	99.2
(4)	Hot Rinse - Water	170°	84.4	95.4	99.7
(5)	Hot Rinse - Water	170°	85.4	96.1	100
(6)	Hot Rinse - Water	170°	85.6	96.2	-
(7)	Sour - 3% Citric Acid	110°	98.2	97.5	-
(8)	Rinse - Water	110°	99.8	97.5	-

* General procedure given in an article by H. W. Gehm on
"Volume Characteristics and Disposal of Laundry Wastes,"
Sewage Works Journal, Vol. 16, No. 3, May 1944, p. 575.
No solution strengths were specified in the article.

and the overall decontamination of Sr^{89} would have been unsatisfactory had it not been for the citric acid treatment. The washing soda probably precipitated strontium (present in significant amount because of the high isotopic dilution) as a carbonate, while an insoluble strontium soap probably formed during the sudsing operations.

Oak Ridge Procedure

The second procedure tried was one in use at the Oak Ridge National Laboratory in 1950.^{4/} Citric acid and Igepal were the principal agents used in this procedure, specifically designed for cleaning radioactive contaminated clothing (other than khaki uniforms and rubber and leather garments). The procedure called for 11 steps, as shown in Table 2, but only six were required in runs with Sr^{89} to remove 100 per cent of the contamination.

No appreciable differences were noted in the use of tap water and demineralized water in the wash solutions and rinses, except in the initial rinse. Here tap water was considerably more effective than demineralized. Actually, it would probably have made little difference in the overall decontamination efficiency of the procedure if this opening rinse had been omitted entirely.

A test run in which Rinso was substituted for the non-ionic Igepal gave essentially the same results as those reported in Table 2, Run 2.

^{4/} McAlduff, H. J., "Review and Outline of Present Laundry Procedure at ORNL", AEC Publication ORNL-600, May 31, 1950, p.6.

Table 2

REMOVAL OF Sr^{89} FROM COTTON CLOTH BY
OAK RIDGE NATIONAL LABORATORY PROCEDURE (1950)

Level of Sr^{89} contamination: 3400-3500 c/m/sample

ORNL (1950) Procedure	Temp. of Solution	Duration, Minutes	Cumulative Percent Removal of Sr^{89}	
			Run 1 ⁺	Run 2 ⁺⁺
(1) Rinse	120° F	4	66.3	45.2
(2) Citric Acid - 6%	180°	8	96.8	95.5
(3) Hot Rinse	180°	4	97.9	99.1
(4) Suds - 1% Igepal	180°	8	99.5	99.7
(5) Citric Acid - 3%	180°	8	99.9	99.9
(6) Hot Rinse	160°	4	100	100
(7) Suds - 0.5% Igepal	180°	8	-	-
(8) Hot Acid	180°	4	-	-
(9) Hot Rinse	160°	4	-	-
(10) Rinse	140°	4	-	-
(11) Rinse	80°	4	-	-

+ Tap water used in all solutions and rinses in Run 1.

++ Demineralized water used in all solutions and rinses in Run 2.

Note: A demineralized water run using Rinso in place of Igepal gave results fairly similar to those shown for Run 2.

Army Quartermaster Corps Procedure

A short formula devised by the Army Quartermaster Corps^{5/} for field use was tested next. Four different agents were involved here: a detergent, citric acid, Versene, and a sour. In field decontamination tests the QMC reported that complexing agents were essential in obtaining adequate decontamination of clothing, and that alkali had to be added to the detergent if the clothing contained a greasy soil.

Good results were obtained with this short formula, as shown by Table 3. A 0.5 per cent Nacconol solution was used here for the "break" and was fairly effective with Sr^{89} and P^{32} . Succeeding treatments with the complexing agents resulted in 100 per cent removal of the Sr^{89} and 99.5 per cent removal of the P^{32} . With Y^{91} , however, neither Nacconol nor citric acid proved overly effective. Despite this, complete removal of Y^{91} was accomplished because of the Versene treatments included in the procedure.

National Bureau of Standards Procedure

A fourth procedure tested was one suggested by the National Bureau of Standards for general decontamination of clothing.^{6/} The only active agents specified were citric acid and a detergent, although an inordinate number of water rinses are included. With this procedure I^{131} was again readily removed, and again initial rinsing with tap

^{5/} Steadman, Col. F. M., and Staff, op. cit., p. 13.

^{6/} National Bureau of Standards Handbook 48, "Control and Removal of Radioactive Contamination in Laboratories", U. S. Dept. of Commerce, Wash. 25, D. C., Dec. 15, 1951, p. 10.

Table 3

REMOVAL OF RADIOACTIVE CONTAMINANTS
FROM COTTON CLOTH BY ARMY QMC PROCEDURE (1951)

Test Conditions:

Duration of all operations except rinses: 5 minutes

Duration of rinses: 3 minutes

Tap water used in all solutions and rinses

Level of contamination: Sr⁸⁹: 2400-2800 c/m/sample

Y⁹¹: 4200-4800

P³²: 4300-5000

Army QMC Procedure 77A	Temp. of Solution	Cumulative Percent Removal		
		Sr ⁸⁹	Y ⁹¹	P ³²
(1) Suds - 0.5% Nacconol	95° F	78.8	39.4	80.9
(2) Citric Acid - 3%	140°	90.5	66.6	93.5
(3) Citric Acid - 1.5%	140°	95.4	84.1	95.1
(4) Versene - 1.0%	140°	98.8	98.7	97.8
(5) Versene - 0.5%	140°	99.3	99.5	97.8
(6) Rinse	140°	99.8	99.8	99.2
(7) Rinse	120°	100	100	99.4
(8) Sour - 0.1% Acetic Acid	75°	-	-	99.5

water was considerably more effective than demineralized water in the removal of Sr^{89} . In fact, the use of tap water in all solutions throughout the procedure gave better results with strontium than a run in which demineralized water was used exclusively. Although the complete 12-step procedure was followed with P^{32} , only 95.7 per cent removal was obtained. It is significant that the final five water rinses succeeded in increasing the P^{32} removal only one per cent beyond that accomplished by the first seven steps. These results are all presented in Table 4.

Water Rinsing Tests

Tests were then conducted in which cloths contaminated by Sr^{89} , P^{32} , and I^{131} were subjected to repeated rinsing with water alone at room temperature. As shown by Table 5, comparatively good removals of I^{131} and Sr^{89} (95.3 to 99.5 per cent) were obtained upon completion of seven to nine rinse cycles, while removals of P^{32} were less satisfactory (86.8 to 88.1 per cent). It is noteworthy that in no cases were removals of 100 per cent obtained.

With regard to P^{32} and I^{131} , demineralized water was found to be very slightly superior to tap water as a decontaminant. The opposite tendency was observed with Sr^{89} in the preceding tests.

Table 4

REMOVAL OF RADIOACTIVE CONTAMINANTS FROM
COTTON CLOTH BY NATIONAL BUREAU OF STANDARDS
PROCEDURE

Test Conditions:

Duration of each wash and rinse: 5 minutes
 Temp. of all wash and hot rinse solutions: 170° F
 Level of contamination: Sr⁸⁹: 2100-3700 c/m/sample
 P³²: 2800
 I¹³¹: 2900

National Bureau of Standards Procedure	Cumulative Percent Removal			
	Sr ⁸⁹		P ³²	I ¹³¹
	Run 1†	Run 2††		
(1) Hot Rinse	61.3	42.7	42.0	89.9
(2) Hot Rinse	85.4	53.3	58.1	97.4
(3) 3% Citric Acid Wash	95.9	86.3	68.6	98.0
(4) Hot Rinse	98.3	92.6	71.6	98.8
(5) Hot Suds - 0.3% Rinso	99.3	98.0	89.3	99.9
(6) Hot Rinse	99.7	98.5	94.0	-
(7) 1.5% Citric Acid Wash	100	99.5	94.7	-
(8) Hot Rinse	-	99.5	95.1	-
(9) Hot Rinse	-	99.5	95.5	-
(10) Hot Rinse	-	-	95.6	-
(11) Cold Rinse	-	-	95.7	-
(12) Cold Rinse	-	-	95.7	-

† Tap water used in all solutions and rinses in Run 1 with Sr⁸⁹, and in the runs with P³² and I¹³¹.

†† Demineralized water used in all solutions and rinses in Run 2 with Sr⁸⁹.

Table 5

REMOVAL OF SR⁸⁹, I¹³¹, AND P³²
FROM COTTON CLOTH BY RINSING WITH WATER

Test Conditions:

Duration of each rinse: 5 minutes
Temperature of water: 75° F.
Level of contamination: 1000-2000 c/m/sample

<u>Rinse Number</u>	<u>Percent Removal by Tap Water</u>			<u>Percent Removal by Demineralized Water</u>	
	<u>Sr⁸⁹</u>	<u>I¹³¹</u>	<u>P³²</u>	<u>I¹³¹</u>	<u>P³²</u>
1	58.7	66.2	67.0	72.6	72.7
2	84.5	78.5	76.5	84.4	80.2
3	94.4	80.5	80.6	88.7	82.1
4	98.3	89.3	81.3	91.8	84.5
5	98.8	89.7	85.0	92.4	86.5
6	99.4	90.3	86.0	93.8	86.7
7	99.5	91.2	86.0	94.8	88.0
8	-	91.3	86.8	95.3	88.1
9	-	96.6	86.8	95.3	88.1

Discussion of Results

The tests indicate that standard commercial laundering procedures are not ideally suited to the removal of all types of contaminants from clothing, for the soaps which are ordinarily used may tend to precipitate certain of the metallic isotopes. Multiple rinsing with water alone removes a high percentage of water-soluble contamination from cloth, but procedures involving the use of complexing agents and specially designed to remove radioactive contamination as well as soil are evidently required to effect highest possible removals of some isotopes. A detailed study of the action of various types of agents on different isotopes is presented in the following Section.

IV. DECONTAMINATING EFFICIENCY OF VARIOUS DETERGENTS AND SEQUESTERING AGENTS

Representative types of the various classes of detergents and sequestering agents used in laundering and decontamination work were tested on six different isotopes, four metals and two non-metals. Cloth samples were immersed separately in solutions of Sr^{89} , Y^{91} , Ce^{141} , Fe^{59} , P^{32} , and I^{131} , then subjected to a four-step laundering procedure consisting of a 10-minute wash, 5-minute water rinse, 10-minute wash with fresh solution, and another 5-minute rinse. All of the laundering operations were performed at room temperature (about 75° F.), and counts were made after each step. In runs with the metallic isotopes, three per cent concentrations of the various agents were used, while one per cent strengths were utilized with the non-metallic isotopes.

The results of these tests, shown in Figures 4 through 9, are indicative of the performance of the different agents used individually and under essentially identical conditions in removing water-soluble contaminants from cotton cloth. Small differences in removal efficiency at the higher levels of decontamination could mean the difference between successful decontamination and rejection of an article of clothing for storage or return for further laundering. Therefore, the data obtained are presented in the form of bar graphs plotted on an expanding percentage removal scale so that small variations in removal efficiency in the important 90-100 per cent range are not obscured.

Removal of Strontium 89

Efficiencies of 99.8 to 100 per cent were obtained with ammonium citrate, Calgon (sodium hexametaphosphate), CP Cleaner, sodium citrate, and Versene (tetra sodium salt of ethylene diamine tetra acetic acid) in the removal of Sr^{89} from cotton cloth. All of the above substances are complexing agents which tend to react chemically with the strontium present and bind it into a soluble complex which can be readily rinsed out of the cloth. The action is successful if the stability of the complex formed is great enough to overcome the forces binding the strontium ions to the cotton fibers. Initial removal of the isotope is not enough; re-adsorption and re-combination must be prevented if effective decontamination is to result.

Slightly lower removal efficiencies, 98.7 to 99.5 per cent, were obtained with Radiacwash (which contains Versene), citric acid, Nacconol NR (an alkyl aryl sulfonate), and Roccal (alkyl dimethyl benzyl ammonium chloride). Igepal CO (alkyl phenoxy polyoxyethylene ethanol), a non-ionic detergent, and Rinso, a soap compound, were both inferior with regard to Sr^{89} decontamination. Du Rite (Formula 85), a locally produced and inexpensive anionic detergent, actually proved detrimental, for less Sr^{89} was removed than with demineralized water. Qualitative tests indicated that this detergent contains a considerable percentage of sodium carbonate as an alkaline builder, which would cause precipitation of strontium under the high pH conditions prevailing.

FIG. 4 - REMOVAL OF Sr^{89}
FROM COTTON CLOTH BY
VARIOUS DECONTAMINATING AGENTS

With demineralized water, a removal efficiency of 72 per cent was noted, 55 per cent of the contamination being removed in the initial operation. Tap water and the non-ionic Igepal also removed a similar amount in the first step, leading us to believe that some 55 to 60 per cent of the contamination originally present was in the form of $\text{Sr}(\text{NO}_3)_2$ salt deposited on the cloth as a result of evaporation of the water during drying. The demineralized water readily dissolved this salt, as did other agents, but removed very little more of the strontium in the succeeding operations. Tap water, on the other hand, in four steps removed 98.3 per cent of the contamination. To see whether the bicarbonate alkalinity present in the tap water (40 p.p.m., expressed as CaCO_3) was responsible for this, a separate test was run in which a three per cent solution of sodium bicarbonate was used. Results were only slightly better than with demineralized water. It is most probable then that the strontium which remained after the first wash was either adsorbed or more likely chemically combined with the free carboxyl groups present in cotton fibers, and that it was removed primarily by exchange with the di- and tri-valent metallic ions present in the tap water (mainly calcium and magnesium ions, with a very slight amount of residual aluminum from coagulation in the water treatment plant, giving a total hardness of 55 p.p.m., expressed as CaCO_3).

Removal of Yttrium 91

Good results were obtained with complexing agents in removing

FIG. 5 - REMOVAL OF Y⁹¹
FROM COTTON CLOTH BY
VARIOUS DECONTAMINATING AGENTS

Y^{91} from cotton cloth. Ammonium citrate, Calgon, CP Cleaner, and Versene removed 98.3 to 99.7 per cent of the carrier-free isotope. Sodium bicarbonate and the anionic detergents Rinso (sodium salt of a fatty acid) and Nacconol NR (about 60 per cent inorganic salt, mainly sodium sulfate) also did a fairly good job. The very high concentrations of sodium ions present in three per cent solutions of these substances would certainly tend to replace the comparatively few yttrium ions present on the cloth, even though the yttrium is tri-valent.

The poor results with tap water might be anticipated in the case of Y^{91} , since the element is tri-valent and therefore would not tend to be replaced to any appreciable extent by the relatively low concentrations of predominantly di-valent metallic ions present in the water. Citric acid, at a pH value close to 2, was of little value. Yttrium apparently does not readily enter into a soluble citrate complex when unionized H_3cit and H_2cit^- ions are the dominant forms present, as it does with ammonium citrate at a pH of about 5, when $Hcit^-$ ions are present in greatest number. Demineralized water, Igepal, and Roccal, unable to disrupt the attractive forces existing between the Y^{91} and the cotton fibers, were all ineffective in their action.

Removal of Cerium 141

Virtually the same removal efficiencies with complexing agents were noted in the cerium tests as with yttrium. Ammonium citrate, Calgon, CP Cleaner, and Versene again were the top

FIG. 6 - REMOVAL OF Ce^{141}
FROM COTTON CLOTH BY
VARIOUS DECONTAMINATING AGENTS

decontaminating agents of those tested, removing 99.1 to 99.5 per cent of the tri-valent Ce^{141} . Sodium citrate also gave good results, while sodium bicarbonate and citric acid were a little less efficient.

Removal of cerium was generally slightly better at neutral or lower pH than was that of yttrium, as evidenced by the results with citric acid, Nacconol (pH 4.7), and Igepal (pH 6.0 in the demineralized water solution used). Rinso at a pH of 10.2, was somewhat less effective than with yttrium.

Removal of Iron 59

The ferric ion, like the other metals tested, was effectively removed (97.6 to 98.7 per cent) from cotton cloth by the complexing action of both Calgon and ammonium citrate. Sodium citrate and citric acid were nearly as effective, and fair removals of the isotopically diluted iron were observed with all of the other agents tested. The detergents were about on a par at 80 per cent efficiency.

The chelating action of regular Versene was found to be considerably less with Fe^{59} than with the previously studied di- and tri-valent metal ions. Therefore, the specialized agent Versene Fe-3 Specific was tried and the removal efficiency increased from 85.9 to 96.2 per cent. In repeated tests, however, there was considerable variability in the action of both forms of Versene on iron.

FIG. 7 - REMOVAL OF Fe^{59}
FROM COTTON CLOTH BY
VARIOUS DECONTAMINATING AGENTS

Removal of Phosphorus 32

Phosphorus was rather difficult to remove completely. The maximum efficiency was 96.2 per cent, a level attained by both Versene and CP Cleaner. Radiacwash, Rinso, and sodium bicarbonate were slightly less effective. Water rinsing alone, using both tap and demineralized water, removed 82 per cent of the contamination.

Under the conditions of contamination, it is likely that the P^{32} was adsorbed mainly in the form of $H_2PO_4^-$ ions. Since this ionic form predominates in the pH range of about 3 to 6, it is not unexpected that agents which produced or were present in solutions of pH less than neutral (citric acid, ammonium citrate, Roccal, Nacconol, and Igepal) were of little value in the removal of P^{32} .

Calgon, at a pH of 6.5, was likewise of little help. In a separate test, however, in which Calgonite (sodium hexametaphosphate plus alkaline silicates) was substituted for the Calgon, the pH rose to 11.9 and the efficiency of removal went up to 96.5 per cent. Hydroxyl ions, present in high concentrations under highly alkaline conditions, evidently tend to replace the adsorbed phosphate ions. A strong negative potential created at the cotton fiber surfaces by adsorption of sufficient numbers of the OH^- ions would tend to repel the strongly negative $HPO_4^{=}$ and $PO_4^{=}$ ions, which would be the predominant phosphate species present at high pH. The surface of the cloth would thus be maintained comparatively free of P^{32} contamination. The negative potential is attributed

FIG. 8 - REMOVAL OF P³²
FROM COTTON CLOTH BY
VARIOUS DECONTAMINATING AGENTS

30

primarily to the adsorption of hydroxyl ions rather than anions from the detergents, since the effect appears to be common to all of the alkaline agents, irrespective of the nature or concentration of the anions.

Removal of Iodine I^{131}

Contamination due to I^{131} was more completely eliminated from cotton than that due to P^{32} . Sodium citrate and potassium iodide solutions afforded removals as high as 99.0 per cent, and only relatively minor variations in decontaminating efficiency were observed among the various agents tested. For practical purposes, however, the KI would probably have to be ruled out, for brownish iodine stains were produced on the white cloth samples upon drying.

Chlorox (5.25 per sodium hypochlorite by weight) was tried in 0.3 and in 1.0 per cent solutions to see if an oxidizing agent would be effective in removing I^{131} . Results were good, but no better than those obtained with sodium citrate, Calgon, and Nacconol. Citric acid proved to be somewhat of a detriment, because of the low pH. An earlier study^{7/} showed that highly acid conditions favor the adsorption of I^{131} by textile fibers. Actually, there seems to be only a slight advantage in using any agent other than water, since 95.2 per cent of the I^{131} present, presumably as soluble NaI, was rinsed out by demineralized water alone.

^{7/} Talboys, A. P., and Buckingham, R. A., "Contamination Tendencies of Textile Fibers with Respect to I^{131} ", AEC Progress Report JHUL-1, Johns Hopkins University, June 15, 1952 (Unpublished).

FIG. 9 - REMOVAL OF I^{131}
FROM COTTON CLOTH BY
VARIOUS DECONTAMINATING AGENTS

Discussion of Results

Removal of Metals: Certain complexing agents are outstanding in their ability to remove metallic isotopes from cotton cloth. Calgon, Versene, and ammonium citrate all were extremely effective in tests with Sr^{89} , Y^{91} , Ce^{141} , and Fe^{59} . Sodium citrate was only slightly less efficient. Any of these four agents could probably be interchanged in a laundering process with essentially the same results. In the case of iron contamination, it might be advantageous to substitute Versene Fe-3 Specific for the regular form, or a mixture of the two types, marketed as Versene Fe-3, could be used.

Results with the commercial preparation CP Cleaner were excellent, and there is no doubt that an efficient complexing agent is included in the mixture. Similarly, Radiacwash seems to be largely dependent upon its Versene content for its effectiveness. While both agents were good, no advantages were apparent over the best of the complexing agents when used by themselves in removing water-soluble metallic radioisotopes.

Citric acid, one of the most popular agents used in the decontamination of clothing, was in general inferior to all of the aforementioned substances in the laundering tests performed here. Apparently somewhat less acid conditions are required for the metallic isotopes tested to readily form soluble citrate complexes. It must be borne in mind, however, that other factors such as concentration of the agent, temperature of the wash bath, and

specificity of action at low pH on certain metals could alter this picture to some extent. Higher temperatures might also, in some cases, improve the performance of soaps such as Rinso.

The detergents, as a group, were only moderately effective as decontaminants. Nacconol, a synthetic anionic detergent, was best, while Rinso was at least as good as the non-ionic Igepal. The cationic sanitizing agent Roccal, which cannot react with heavy metals, showed no promise as a decontaminating agent.

Sodium bicarbonate, adjudged the generally most suitable decontaminant for water-soluble uranium salts in the Rochester study, gave only mediocre results in the tests performed here.

Removal of Non-Metals: With regard to removal of the non-metallic isotopes, rinsing with plain water was generally more effective than in the tests with the metals. Nevertheless, in every instance residual traces of activity were left after the four-step laundering operation, regardless of the agent employed with the water as a decontaminant. The alkaline agents, Calgonite, Versene, CP Cleaner, Radiacwash, and Rinso, were more effective than acidic solutions against the P^{32} .

While few differences were noted among the agents used in the I^{131} tests, sodium citrate and Calgon appeared to have a very slight superiority over the others. This could be merely experimental error, however, for the complexing agents in general showed

no consistent superiority over either detergents or water. As with P^{32} , acidic agents like citric acid should be avoided since they tend to promote adsorption rather than desorption.

General: It is evident from a study of the bar graphs that the initial laundering operation removed by far the greatest proportion of the removable contamination in practically every case. Water-soluble salts deposited on or within the cloth samples and ions weakly adsorbed on the soil or fibers are largely removed in this step by almost any type of solution. However, the more effective the decontaminating agent used, the greater is the removal of firmly bound ions accomplished in this initial washing step. The following rinse serves to wash out and dilute the radioisotope-bearing decontaminating solution absorbed by the cloth during the washing. The actual number of laundry cycles required will depend upon the degree of decontamination desired as well as the proper choice of decontaminating agents. Effects of other factors, such as the form and extent of contamination and variations in laundering technique, are discussed in the following Sections.

V. IMPORTANCE OF CONTAMINATING CONDITIONS

If a certain decontaminating agent is selected for use in laundering, the question arises as to whether the efficiency of the agent will be equally high regardless of the conditions of contamination. In other words, will success of the laundering operation be variable, depending upon whether contamination of the cloth is caused by spilling or splashing of radioactive solutions or by mechanical occlusion of radioactive dust particles by the fibers; whether contamination is of a high or low level; whether the cloth is clean or dirty prior to contamination; or whether the clothing has been previously laundered or contaminated. The following tests were designed to provide some information along these lines.

Removal of Sr^{89} and Fe^{59} Precipitates and Dusts

In order to compare efficiency of removal of radioactive solutions, precipitates, and dusts, a number of cloths were contaminated by immersing them in Sr^{89} solutions at pH 6 and pH 11-12, respectively. Other cloths were placed in Sr^{89} solutions adjusted to pH 12.5 with sodium hydroxide, and sufficient stable SrCl_2 salt was added to produce a visible white precipitate which settled onto the cloths. Still others were contaminated with a dry, finely ground ash in which Sr^{89} had been dispersed as uniformly as possible.

Little difficulty was experienced with any of the agents in removing a high proportion of the dry, mechanically occluded contamination. Even demineralized water removed 92.7 per cent of the Sr^{89} present in the ash, as compared to 72.4 per cent of the solution contamination and only 42.4 per cent of the precipitated strontium. Versene proved capable of removing 100 per cent of all forms of the strontium contamination. Ammonium citrate and citric acid, although very slightly less effective in these tests than Versene, likewise acted on the different forms of contamination with essentially equal facility.

A similar set of runs was made with Fe^{59} . A slurry of diatomaceous earth and active FeCl_3 solution was evaporated to dryness, pulverized, and applied to some of the cotton cloths. Other samples were contaminated by FeCl_3 solutions and precipitated $\text{Fe}(\text{OH})_3$, respectively.

Of the three forms of contamination, the Fe^{59} -bearing dust was in general most easily removed. Rinso was outstanding in removal of the dust. This same agent was also found to be very efficient in removing insoluble uranium oxide compounds from cloth in the Rochester study. It is evident, then, that soap, because of its suspending and dispersing power, is most effective in radioactive decontamination where particulate matter must be washed out of clothing.

Calgon, the most effective all-around agent used in the iron tests, removed 100 per cent of the precipitated Fe^{59} . Citric acid also showed to good advantage in this test, while the alkaline agents, sodium citrate, Rinso, and Versene, were unable to dissolve a large proportion of the hydroxide precipitate. Versene T, recommended for use in caustic solution, was not used here but probably would have improved upon the results obtained with regular Versene. Nacconol was completely ineffective, removing only a few per cent of the activity present on the cloth.

Results of both the Sr^{89} and Fe^{59} tests are shown in Table 6.

Effect of pH of I^{131} Solution on Removal Efficiency

A previous study had demonstrated that fabrics immersed in I^{131} solutions tend to adsorb the I^{131} most strongly under low pH conditions. To find out if this greater adsorptive attraction would have any effect on the laundering results, cloths were contaminated at pH 3 and at pH 6, then washed with various concentrations of Calgon and Nacconol. In all cases, the samples which were contaminated at low pH were more difficult to decontaminate. Somewhat better removals were obtained with these samples, however, when higher concentrations of Calgon and Nacconol were used. Results of these tests are shown in Table 7.

Table 6

REMOVAL OF Sr^{89} AND Fe^{59} PRESENT IN VARIOUS
FORMS ON COTTON CLOTH

Laundry cycle used: 10 min. wash, 5 min. rinse,
10 min. wash, and 5 min. rinse

A. Strontium 89

<u>Decontaminating Agent</u>	<u>Percent Removal of Sr^{89} from Cloth Contaminated by:</u>			
	<u>Sol'n at pH 6</u>	<u>Sol'n at pH 11-12</u>	<u>Prec. at pH 12.5</u>	<u>Sr^{89}-Bearing Dust</u>
(1) Amm. Citrate (1%)	100	99.8	99.9	98.1
(2) Citric Acid (1%)	97.8	-	99.8	95.1
(3) Demin. Water	72.4	-	42.4	92.7
(4) Tap Water	98.3	-	35.7	95.8
(5) Versene (1%)	100	100	100	100

B. Iron 59

<u>Decontaminating Agent</u>	<u>Percent Removal of Fe^{59} from Cloth Contaminated by:</u>		
	<u>FeCl_3 Sol'n</u>	<u>$\text{Fe}(\text{OH})_3$ Prec.</u>	<u>Fe^{59}-Bearing Dust</u>
(1) Calgon (3%)	98.7	100	89.5
(2) Citric Acid (3%)	93.0	97.6	93.8
(3) Nacconol (1%)	74.3	4.3	89.8
(4) Rinso (1%)	66.1	32.4	97.6
(5) Sodium Citrate (3%)	94.8	68.5	87.4
(6) Tap Water	63.4	20.7	84.0
(7) Versene (1%)	84.1	49.9	93.2

Table 7

EFFECT OF pH OF CONTAMINATING
SOLUTION ON REMOVAL OF I¹³¹ FROM COTTON CLOTH

Test Conditions:

Laundry cycle used: 10 min. wash, 5 min. rinse
10 min. wash, and 5 min. rinse
Demineralized water used in all solutions and rinses
Temp. of all solutions: 75° F.
Level of Contamination: pH 6: 2000-3000 c/m/sample
pH 3: 1500-2000

<u>Decontaminating</u> <u>Agent</u>	<u>Conc.,</u> <u>Percent</u>	<u>Percent Removal of I¹³¹ from Cloth</u> <u>Contaminated by Solution at:</u>	
		<u>pH 6</u>	<u>pH 3</u>
(1) Calgon	0.3	99.1	83.7
	1.0	98.6	87.9
	3.0	98.5	90.8
(2) Nacconol	0.3	98.1	75.6
	1.0	98.9	82.5
	3.0	97.5	84.1

Effect of Level of Contamination on Removal Efficiency

Further tests were made in which the concentration of activity in the contaminating solutions was varied. With carrier-free I^{131} , increasing the concentration resulted in increased contamination of the cloths and decreased percentage removals in the laundering operations. For instance, at a contamination level of 1256 c/m/sample, 94.0 per cent of the I^{131} was removed with Nacconol, while at 24,324 c/m, only 78.4 per cent came out of the cloth. A similar although less marked trend was observed when tap water was used in place of the Nacconol.

In tests with a metallic isotope, carrier-free Ce^{141} , removal efficiencies were essentially unchanged despite a 35-fold variation in count on the contaminated samples.

Still greater ranges of contamination were involved in the strontium runs, for contaminating solutions containing carrier-free Sr^{89} , Sr^{89} with an isotopic dilution ratio of about 10^8 parts inactive to one part active strontium, and isotopically diluted Sr^{89} with an additional 5 ppm. of stable $SrCl_2$, respectively, were used. With approximately counts of radioactivity on each cloth, lowest percentage removals were obtained in the case of samples contaminated by the carrier-free isotope when Nacconol and tap water were used as decontaminating agents. With Versene also, percentage removals increased with the total amount of strontium present on the cloths.

The results of these tests, presented in Table 8, indicate that in the case of metallic isotopes, gross contamination of cotton clothing can in all probability be reduced to normal tolerance levels if effective agents are employed.

Removal of Sr^{89} and P^{32} from Clean and Soiled Samples

Since protective clothing may oftentimes be soiled as well as contaminated, tests were made to check removals of Sr^{89} and P^{32} from clean cloths, from naturally soiled samples, and from samples laundered prior to contamination.

The clean cloths, cut from unexposed portions of discarded lab coats which had never been laundered, were easiest to decontaminate. Percentage removals did not differ greatly, however, among the three categories of samples tested, as shown by Table 9. This is particularly noteworthy because the soiled samples which were used were extremely dirty. Cloths laundered previous to contamination appeared to retain the P^{32} more strongly than did either the clean or soiled samples.

Effect of Repeated Contamination on Removals

Another important factor to consider is build-up of residual radioactivity on a garment repeatedly contaminated and decontaminated. In addition, repeated soiling and washing may cause tendering and progressive deterioration of the cloth, even after a few cycles, and may change the fabric characteristics sufficiently to influence detergent processes.

Table 8

EFFECT OF LEVEL OF CONTAMINATION ON REMOVAL
OF I¹³¹, CE¹⁴¹, AND SR⁸⁹

Laundry cycle used: 10 min. wash, 5 min. rinse,
10 min. wash, and 5 min. rinse

<u>Decontaminating Agent</u>	<u>Contaminant</u>	<u>Contamination, c/m</u>		<u>Percent Removal</u>
		<u>Initial</u>	<u>Final</u>	
<u>A. Iodine</u>				
(1) Tap Water	I ¹³¹ (C.F.)*	1519	162	89.3
		4303	545	87.3
		8299	1164	86.1
		13,879	2332	83.5
(2) Naconol (1%)	I ¹³¹ (C.F.)	1256	75	94.0
		3890	231	94.0
		8979	728	91.8
		12,060	2238	81.5
		24,324	5269	78.4
<u>B. Cerium</u>				
(1) Versene (3%)	Ce ¹⁴¹ (C.F.)	1638	16	99.1
		21,000	178	99.2
		56,840	406	99.2

* C.F.: carrier-free

Table 8 (continued)

<u>Decontaminating Agent</u>	<u>Contaminant</u>	<u>Contamination, c/m</u>		<u>Percent Removal</u>
		<u>Initial</u>	<u>Final</u>	
<u>C. Strontium</u>				
(1) Tap Water	Sr ⁸⁹ (C.F.)	3438	1409	59.2
	Sr ⁸⁹ (I.D.)**	3172	175	94.4
	Sr ⁸⁹ (I.D.)	3498	159	95.5
	+ 5 ppm SrCl ₂			
(2) Naconol (1%)	Sr ⁸⁹ (C.F.)	3348	901	73.2
	Sr ⁸⁹ (I.D.)	3091	71	97.7
	Sr ⁸⁹ (I.D.)	3314	277	91.6
	+ 5 ppm SrCl ₂			
(3) Versene (1%)	Sr ⁸⁹ (C.F.)	2372	127	94.5
	(1%) (C.F.)	12,629	487	96.1
	(3%) (C.F.)	54,000	230	99.6
	(3%) (I.D.)	44,410	0	100

** I.D.: isotopically diluted

Table 9

REMOVAL OF SR⁸⁹ AND P³² FROM CLEAN, SOILED, AND PREVIOUSLY
LAUNDERED COTTON CLOTH

Test Conditions:

Clean cloth: relatively clean and white, unlaundered
Soiled cloth: very dirty, naturally soiled
Prev. laundered cloth: washed with Rinso
Demineralized water used in all solutions and rinses
Temp. of all solutions: 75° F.
Level of contamination: Sr⁸⁹: 1600-2400 c/m/sample
P³²: 2100-3200

<u>Decontaminating Agent</u>	<u>Laundry Cycle</u>	<u>Cumulative Percent Removal from Cloths</u>		
		<u>Clean</u>	<u>Soiled</u>	<u>Prev. Laundered</u>
<u>A. Strontium 89</u>				
(1) CP Cleaner (3%)	Wash & Rinse	100	98.9	99.7
(2) Versene (3%)	Wash & Rinse	100	99.6	99.7
<u>B. Phosphorus 32</u>				
(1) CP Cleaner (3%)	Wash & Rinse #1	86.7	82.8	76.3
	Wash & Rinse #2	90.7	88.1	84.8
(2) Rinso (1%)	Wash & Rinse #1	88.8	79.4	77.0
	Wash & Rinse #2	92.8	86.3	84.1

In tests with Sr^{89} , Versene and tap water were found to be equally effective in removing isotope from samples exposed only once to Sr^{89} solution and from those recontaminated following two successive contamination-decontamination cycles. When Rinso was used, however, a continual accumulation of strontium resulted, along with continually decreasing removal efficiencies. To a lesser extent this same cumulative tendency was noted in tests with P^{32} , in which Rinso, Nacconol, and Versene were used. The data collected in these runs are presented in Table 10.

Discussion of Results

Strontium present in finely divided ash ground into cotton cloth was washed from the samples quite readily by all solutions tested. Since the ash was applied in the dry state, there was little opportunity for ionic adsorption or chemical combination of the Sr^{89} to take place. Therefore, decontamination was accomplished primarily by solution of the water-soluble strontium salt occluded on the fabric along with the ash. Still, complete removal was obtained only with the strong complexing agent Versene, which so effectively tied up the strontium ions formed upon solution of the salt that they were incapable of adsorbing on the cloth.

In the case of Fe^{59} , a portion of the isotope present apparently was attached to the diatomaceous earth particles, for removal of the contamination was more dependent upon removal of the particles themselves than in the case of Sr^{89} . Because of this, Rinso, a soap, proved to be the best decontaminant tried.

Table 10

EFFECT OF REPEATED CONTAMINATION ON REMOVAL EFFICIENCIES

Test Conditions:

Laundry cycle: 10 min. wash, 5 min. rinse, 10 min. wash, and 5 min. rinse
Cloths recontaminated after each laundry cycle by immersion in active solution
for 20 minutes

Demineralized water used in all solutions and rinses except in tap water run
Temperature of all solutions: 75° F.

<u>Decontaminating Agent</u>	<u>Laundry Cycle #1</u>			<u>Laundry Cycle #2</u>			<u>Laundry Cycle #3</u>		
	<u>c/m Before</u>	<u>c/m After</u>	<u>% Re- moval</u>	<u>c/m Before</u>	<u>c/m After</u>	<u>% Re- moval</u>	<u>c/m Before</u>	<u>c/m After</u>	<u>% Re- moval</u>
<u>A. Phosphorus 32</u>									
(1) Nacconol (0.3%)	5160	795	84.5	3807	827	78.3	4335	1175	72.8
(2) Rinso (0.3%)	4375	215	95.0	4099	471	88.6	2917	454	84.5
(3) Versene (0.3%)	3745	472	87.3	3727	659	82.4	3387	735	78.3
<u>B. Strontium 89</u>									
(1) Nacconol (0.3%)	2329	163	93.0	3169	294	90.8	3429	307	91.1
(2) Rinso (0.3%)	2567	442	83.0	4243	2006	52.3	5674	3615	36.3
(3) Versene (0.3%)	2360	4	99.9	3123	5	99.9	2819	12	99.5
(4) Demineralized Water	2137	1535	28.7	2446	962	60.5	2090	1317	36.5
(5) Tap Water	2083	71	96.5	1390	67	95.1	1505	31	96.7

The particles were apparently "floated" off the fabric to a considerable extent by action of the water alone, but the soap effectively dispersed and stabilized the particles in the solution, thereby preventing their redeposition on the cloth. The complexing agents Calgon and citric acid proved more versatile than soap, however, because of their ability to remove high proportions of the FeCl_3 and $\text{Fe}(\text{OH})_3$ contamination, as well as the Fe-bearing dust, by inactivating the ferric ions as they were liberated upon immersion of the samples in the wash bath.

The main drawback to the wider application of soap in decontamination was demonstrated by the repeated-contamination tests with strontium. The insoluble compound formed by reaction of the soap with the strontium present tenaciously adhered to the fabric and accumulated through successive contamination and decontamination cycles. This same action would probably be duplicated by any of the alkaline earths or heavy metals.

In tests with several different isotopes and agents, removal efficiencies were found to vary somewhat with extent of contamination, pH of contaminating solution, and extent of soiling of the cotton. It is of interest to note that both soiled samples and cloths previously laundered with Rinso to remove soil were not quite as readily decontaminated as clean cloth. On the whole, the results indicate that if sufficient concentrations of efficient and appropriate decontaminating

agents are used, reasonably good removals can be obtained irrespective of the conditions under which contamination occurs. A greater number of laundering cycles may be required in some cases, however, to reach a satisfactorily low level of activity remaining on the cloth.

VI. EFFECTS OF VARIATION IN LAUNDERING TECHNIQUE

The effects of varying concentration of decontaminating agent, temperature of wash bath, duration of wash, loading of the washwheel, and sequence of operations on decontaminating efficiency were investigated. The effect of pre-rinsing with water was also studied in connection with the undesirable phenomenon of cross-contamination.

Concentration of Decontaminating Agent

In normal laundering operations, detergents are usually used in strengths of 0.1 to 0.3 per cent, depending on the hardness of the water, composition of the detergent, extent of soiling of the garments, wash bath temperature, and other factors. Long experience has shown that the use of excessively high concentrations of detergents does not improve washing efficiency nor is it economical. It is customary, however, to use three or even six per cent solutions of decontaminating agents like citric acid in radioactive laundering operations. Such high concentrations result in very strong wastes and often increase the difficulty of treatment. Therefore, to see whether these concentrations are really warranted, laundering tests were made with solutions at 0.3 per cent (simulating ordinary commercial laundering practice), 1.0 per cent, and 3.0 per cent. In several runs, ammonium citrate, citric acid, Du Rite, Igepal, and Nacconol were tried at 6.0 per cent strength.

Listed in Table 11 are the minimum solution concentrations affording maximum removals of Sr^{89} , Y^{91} , Fe^{59} , P^{32} , and I^{131} . On

Table 11

CONCENTRATIONS OF DECONTAMINATING
AGENTS AFFORDING MAXIMUM REMOVALS
OF RADIOACTIVE CONTAMINANTS

<u>Decontaminating</u> <u>Agent</u>	<u>pH*</u>	<u>Solution Concentration in Percent</u> <u>Affording Maximum Removal of:</u>				
		<u>Sr⁸⁹</u>	<u>Y⁹¹</u>	<u>Fe⁵⁹</u>	<u>I¹³¹</u>	<u>P³²</u>
(1) Ammonium Citrate	5.1	3.0	3.0	3.0	1.0	3.0
(2) Calgon	6.5	3.0	3.0	3.0	0.3	0.3
(3) Citric Acid	2.2	6.0	3.0	3.0	1.0	6.0
(4) CP Cleaner	9.7	3.0	3.0	-	1.0	1.0
(5) Du Rite	10.0	6.0	-	3.0	1.0	3.0
(6) Igepal CO	6.0	3.0	0.3	0.3	0.3	0.3
(7) Nacconol NR	4.7	6.0	1.0	3.0	0.3	1.0
(8) Radiacwash	9.8	3.0	-	-	0.3	3.0
(9) Rinso	10.2	1.0	3.0	3.0	3.0	1.0
(10) Sodium Citrate	7.6	3.0	-	3.0	0.3	0.3
(11) Versene (Reg.)	11.5	1.0	3.0	0.3	1.0	0.3

* The pH values given are for 1% solutions of the various agents in demineralized water.

the average, best removals of the metallic isotopes were obtained with the 3.0 per cent solutions. With P^{32} and I^{131} , the 0.3 or 1.0 per cent strengths were generally sufficient. A study of all of the data collected in these concentration tests shows, however, that in the majority of cases removal efficiencies did not vary greatly with concentration of the decontaminating agent.* The few notable exceptions to this last statement are discussed below.

In the removal of P^{32} , the effectiveness of citric acid increased with successively higher concentrations. At first glance this would seem to be contradictory to results reported in Section IV, in which acidic agents were found to be ineffective in removing P^{32} . As the pH drops to 2.2 or lower, however, the phosphate equilibrium is shifted so that more and more of the adsorbed $H_2PO_4^-$ ions are converted to unionized H_3PO_4 molecules, which are not adsorbed to any extent. Even with 6.0 per cent acid though, the removal obtained was only 57.7 per cent, considerably less than with demineralized water.

With the metallic isotopes it was also noted in previous tests that Rinso and the carbonate-containing Du Rite tended to precipitate the isotopes on the cloth. Despite this, the highest concentrations of these detergents generally gave the highest removals. Since this trend was also evident with Nacconol, another sodium ion producing substance, it would appear that the higher the concentration

* A complete tabulation of this data is included in Table A-3 in the Appendix.

of the detergent, the greater exchange takes place between the sodium ions and the metallic ions held by the cloth. In the case of Igepal, which has to rely principally upon its detergent properties rather than ion exchange to remove contaminants, high concentrations were detrimental in practically every instance.

Temperature of Wash Bath

Effects of higher temperatures on removal efficiency of a number of decontaminating solutions were determined in runs with Sr^{89} , Y^{91} , I^{131} , and P^{32} contaminated samples. In the Sr^{89} tests, tap water and Versene were unaffected by temperature, although citric acid was aided to some extent and Rinso to a great extent by the use of hotter solutions. This suggests that rate of reaction of the citric acid with strontium was accelerated slightly. With Rinso, solubility of the soap was undoubtedly increased by the higher temperatures, thereby increasing both the supply of sodium ions and the maximum surface activity attainable with this agent. Both Nacconol and Igepal gave poorer removals at the highest temperature tried, 205°F. , indicating that these agents are soluble to an optimum degree at somewhat lower temperatures.

In the Y^{91} tests, Versene as well as citric acid and Rinso showed improvement with increasing temperature. Since the Y^{91} is tri-valent and carrier-free, it is most likely that the infinitesimal amounts of the isotope actually present are quite firmly bound to the cotton fibers. The higher temperatures may possibly have helped

to decrease the strength of these bonds as well as to increase the rates of reaction involved in formation of the metal-citrate and metal-versenate complexes. Igepal and Nacconol were again found to be less effective at high temperature.

Increased removals of both I^{131} and P^{32} were generally obtained with the hotter solutions, although results with water and Nacconol were somewhat erratic. Since Versene (acting as a surface active agent with the non-metallic isotopes instead of a chelating agent), Rinso, and Igepal all showed such marked improvement with temperature, it would appear as though the attractive forces between the contaminants and the fibers were weakened and adsorption of the surfactants favored by the additional heat energy furnished.

Results of the temperature tests are shown in Figures 10, 11, and 12.

Duration of Wash

Another variable in laundry operation studied was duration of wash. Work done in 1929 at the American Institute of Laundering^{8/} showed that maximum suspension of dirt occurred within five minutes after the correct water level had been reached in the washwheel. It was furthermore demonstrated during the same study that when the correct rinse water level had been attained, uniform suspension of solid dirt occurred within two minutes, a third minute in each rinse serving

^{8/} American Institute of Laundering, "Washing Formulas", Technical Bulletin No. 34, Joliet, Ill., p. 2.

FIG. 10 - EFFECT OF TEMPERATURE
ON REMOVAL OF Sr^{89}

FIG. II - EFFECT OF TEMPERATURE
ON REMOVAL OF Y⁹¹

FIG. 12 - EFFECT OF TEMPERATURE
ON REMOVAL OF I^{131} AND P^{32}

as a factor of safety. Results of tests made here with Sr⁸⁹ contaminated samples, in which the washing period was varied from five minutes to 30 minutes, were in line with the above findings.

It is evident from the data presented in Table 12 that no real advantages were obtained by prolonging the wash period. Removals with Rinso, in fact, tended to be poorest in the 30-minute runs, although slight gains were noted with Nacconol. The more efficient agents, ammonium citrate and Versene, showed no significant variations with time.

Effect of Variation in Loading

In the study at the University of Michigan^{9/} it was found that maximum removal of soil from cotton in domestic clothes washers resulted from a loading of 16 pounds of wash solution per pound of clothing. This 16:1 ratio was closely approximated here by using 25 ml. of decontaminating solution per sample of cloth of average weight 1.58 grams. To examine the effect of lighter loading on radioisotope removals, runs were made using ratios of 50 and 100 ml. as well as 25 ml. per cloth.

The higher ratios used, 32:1 and 64:1, gave generally better removals. With Sr⁸⁹, Nacconal and tap water were aided

^{9/} Ridenour, G. M., "A Bacteriological Study of Automatic Clothes Washing", National Sanitation Foundation, Ann Arbor, Mich., 1952, Appendix B., p. 109.

Table 12

EFFECT OF DURATION OF WASH ON
REMOVAL OF SR⁸⁹ FROM COTTON CLOTH

Test Conditions:

Level of contamination: 1600-3500 c/m/sample

Temp. of solutions: 75° F.

Demineralized water used in all solutions and rinses

Duration of rinse: 5 minutes

Decontaminating Agent	Duration of Wash, Minutes	Cumulative Percent Removal of Sr ⁸⁹			
		Wash #1	Rinse #1	Wash #2	Rinse #2
(1) Ammonium Citrate (0.3%)	5	92.6	94.3	99.1	99.4
	10	89.5	91.8	99.0	99.1
	15	93.1	93.7	99.5	99.6
	30	93.4	93.7	99.4	99.8
(2) Nacconol (0.3%)	5	73.7	76.0	88.5	89.6
	10	70.4	73.3	87.8	88.0
	30	75.7	83.6	89.6	92.4
(3) Rinso (0.3%)	5	65.8	69.1	80.6	83.1
	10	67.4	74.2	82.0	84.0
	30	56.0	57.3	79.8	85.8
(4) Versene (0.3%)	5	96.1	99.4	100	-
	10	94.5	99.1	99.3	99.7
	15	94.0	99.3	100	-
	30	94.8	99.9	100	-

considerably and Rinso moderately by the increased solution volumes. Similar trends were also noted in the tests with I^{131} and P^{32} contaminated samples. These results are shown graphically in Figures 13 and 14.

Much heavier loadings are used in commercial type wash-wheels, however. In fact, in the laundry at Los Alamos, 2:1 ratios are employed.^{10/} Therefore, tests were also made with Sr^{89} contaminated samples using ratios of 16:1, 8:1, 4:1, and 2:1. Because of the appreciable absorption of liquid by dry cloth, all samples were pre-wetted before initiating the laundering procedure. This resulted in sufficient free volume of wash solution in even the most heavily loaded systems to permit a limited "sloshing" action to take place in the initial wash bath.

Again, percentage removals were adversely affected by increased loading, as shown by Table 13. This tendency was observed even when the concentration of Versene in the wash solution was increased in proportion to the loading. The difference in efficiency of removal between the 16:1 and the 2:1 ratio was, however, less than four per cent when Versene was used, and an additional rinse further reduced the discrepancy to around one per cent. It is therefore evident that although lighter loading favors higher removal efficiency, very good results can also be obtained in heavily loaded systems.

^{10/} Christenson, C. W., Chief, Industrial Waste Section, Los Alamos, Personal Communication, Nov. 5, 1953.

FIG. 13 - EFFECT OF VARYING RATIO OF
VOLUME OF SOLUTION TO WEIGHT OF
CLOTH ON REMOVAL OF Sr^{89}

FIG. 14 - EFFECT OF VARYING RATIO OF VOLUME OF SOLUTION TO WEIGHT OF CLOTH ON REMOVAL OF I^{131} AND P^{32}

Table 13
EFFECT OF HEAVY LOADING ON REMOVAL
OF SR⁸⁹ FROM COTTON CLOTH

Test Conditions:

Laundry cycle used: 10 min. wash, 5 min. rinse,
10 min. wash, and 5 min. rinse;
additional 5 min. rinse where noted
Level of contamination: 2000-5500 c/m/sample
All samples wetted with 2.5 ml. water/cloth before laundering

<u>Decontaminating Agent</u>	<u>Loading, Ml Solution/Cloth</u>	<u>Percent Removal of Sr⁸⁹ after: Four-Step Laundry Cycle</u>	<u>Additional Rinse</u>
(1) Demineralized Water	25	64.5	-
	12.5	57.8	-
	6.3	52.7	-
	3.1	48.1	-
(2) Rinso (1% conc. in 1st wash, 0.3% in 2nd for all loadings)	25	93.3	93.5
	12.5	87.1	87.1
	6.3	82.7	84.7
	3.1	81.4	84.5
(3) Versene (3% conc. in 1st wash, 1% in 2nd for all loadings)	25	100	100
	12.5	100	100
	6.3	99.3	99.8
	3.1	96.3	98.7
(4) Versene - 0.5% conc.	25	99.9	100
	1.0%	99.9	100
	2.0%	99.5	100
	4.0%	96.2	99.0

Washing of two contaminated samples simultaneously in the same flask gave essentially the same results as separate washing, provided the loading ratio was kept constant. Also, no effects were noted when moderate changes were made in the degree of agitation provided by the shaking machine. Such variations in technique could be expected to have a considerable effect, however, if the contaminants were present in the form of insoluble particles rather than as ions or water-soluble salts.

Pre-Rinsing and Cross-Contamination

In commercial laundering, soiled clothing is subjected immediately to a washing operation at temperatures low enough to prevent thermal coagulation of albuminous soil, in lieu of pre-soaking or pre-rinsing with either cold or hot water. According to work by Bray on removal of ordinary soil^{11/} from clothing, only 22 per cent removal is accomplished in the first operation by water alone, while 50 per cent removal is obtained with a properly built soap. Nevertheless, some of the decontamination laundering procedures call for initial rinsing with water. To determine the effects of this practice on cross-contamination, contaminated and uncontaminated cloth samples were placed in the same flask and subjected to washing tests with various agents as well as water alone. Results of runs made with Sr^{89} , Y^{91} , P^{32} , and I^{131} contaminated samples are presented in Table 14.

^{11/} American Institute of Laundering, op. cit., p. 3.

Table 14

CROSS-CONTAMINATION IN THE
LAUNDERING OF CONTAMINATED COTTON CLOTH

Test Conditions:

Two cloth samples per flask
Demineralized water used in all solutions and rinses
Temp. of all solutions: 75° F.

<u>Decontaminating Agent</u>	<u>Initial Cont. on Each Cloth, c/m</u>	<u>Activity Present in Counts/Minute on Cloths After</u>			
		<u>Wash #1</u>	<u>Rinse #1</u>	<u>Wash #2</u>	<u>Rinse #2</u>
(1) Nacconol (0.3%)	Sr ⁸⁹ :	1110	89	70	36
		0	45	48	4
	P ³² :	4759	1052	709	531
		0	164	110	72
	I ¹³¹ :	4228	843	470	302
		0	-	43	51
					216
					36
(2) Rinso (0.3%)	Sr ⁸⁹ :	1674	675	517	481
		0	32	12	28
	P ³² :	3747	473	227	245
		0	123	25	15
	I ¹³¹ :	3410	363	186	186
		0	92	52	5
					82
					7
(3) Versene (0.3%)	Sr ⁸⁹ :	1129	48	10	0
		0	21	4	11
	P ³² :	3034	349	240	206
		0	174	61	74
	I ¹³¹ :	3222	479	250	215
		0	131	37	8
					146
					5

Table 14 (continued)

<u>Decontaminating Agent</u>	<u>Initial Cont. on Each Cloth, c/m</u>		<u>Activity Present in Counts/Minute on Cloths after</u>			
			<u>Rinse #1</u>	<u>Rinse #2</u>	<u>Rinse #3</u>	<u>Rinse #4</u>
(4) Demineralized Water	Sr ⁸⁹ :	1251	647	610	461	432
		0	255	251	267	255
	Y ⁹¹ :	3152	1935	1718	1583	1501
		0	188	269	273	248
(4) Demineralized Water	P ³² :	4720	1476	1106	895	842
		0	346	271	207	174
	I ¹³¹ :	3608	402	254	242	206
		0	140	67	50	41
(5) Tap Water	Sr ⁸⁹ :	1255	269	100	38	16
		0	212	95	21	9
	Y ⁹¹ :	3301	2909	2680	2734	2215
		0	129	181	154	192
	I ¹³¹ :	3755	550	345	320	259
		0	135	74	-	34

Adsorption of Sr^{89} and Y^{91} by the originally uncontaminated samples was quite pronounced when no decontaminating agent was present along with the water. This effect is clearly demonstrated by Figure 15, in which both demineralized water and Nacconol were used to remove Sr^{89} from cotton cloth. While a slight amount of cross-contamination occurred even with the detergent, the activity left on each sample after three complete wash-rinse cycles was negligible. With the non-metals, P^{32} and I^{131} , cross-contamination occurred to almost as great an extent when a decontaminating solution was used as with water rinsing.

Effect of Variation in Sequence of Operations

In tests with Sr^{89} and Ce^{141} contaminated samples and Versene, laundry cycles utilizing a pre-rinse with water followed by the usual four-step operation (wash, rinse, wash, rinse) were found to give no better overall removals than the four-step procedure without the pre-rinse.

Then, further tests were made with Ce^{141} , in which the sequence and type of operations within the four-step procedure were varied. According to the results of these runs, shown in Table 15, a wash-wash-rinse-rinse cycle (Sequence B) produced essentially the same effect as a wash-rinse-wash-rinse cycle (Sequence D). In addition, hardly any gain was evident as a result of repeated wash operations. A single wash followed by three rinses (Sequence C) was virtually as effective as cycles consisting of two washes and two rinses (Sequence B) or three washes and a single rinse (Sequence A), when Versene was used as the decontaminating agent.

FIG. 15
CROSS - CONTAMINATION
OF COTTON CLOTH BY Sr^{89}

Table 15

EFFECT OF SEQUENCE OF OPERATIONS ON REMOVAL
OF Ce^{141} FROM COTTON CLOTH

Test Conditions:

Decontaminating agent: Versene, 3% solution in all initial washes; 1% in all subsequent washes

Temp. of solutions: 75° F.

Duration of each wash: 10 minutes

Duration of each rinse: 5 minutes

Level of contamination: 10,000-17,000 c/m/sample

<u>Sequence of Operations</u>	<u>Cumulative Percent Removal of Ce^{141}</u>
A. Wash	92.4
Wash	98.8
Wash	99.3
Rinse	99.4
B. Wash	93.7
Wash	99.1
Rinse	99.6
Rinse	99.8
C. Wash	92.1
Rinse	98.6
Rinse	99.1
Rinse	99.2
D. Wash	92.5
Rinse	98.7
Wash	99.2
Rinse	99.4

Discussion of Results

High concentrations of decontaminating agents are warranted if maximum removals of metallic isotopes are required. If waste treatment difficulties are experienced, however, the solution strengths can be considerably reduced in practically all cases without seriously sacrificing decontaminating efficiency, if the tests made here are any indication. With the non-metallic contaminants, 0.3 to 1.0 per cent concentrations are entirely adequate.

In the report on the Rochester work with uranium, it was stated that no significant differences between cold and hot washing were noted. However, high solution temperatures were found to be generally advantageous in the tests conducted here. Of the decontaminating agents used, only Nacconol seemed to be fully effective in cold water, while most of the others performed best at 170° F. or even higher.

While there is difference of opinion in the literature with regard to optimum washing time for removing ordinary soil, the limited tests made here with Sr⁸⁹ indicate that five-minute washing is sufficient. By keeping loads as light as possible, maximum decontaminating efficiency can be realized in a minimum number of laundering operations. Pre-rinsing with water is of no apparent value with metallic contaminants, and since it tends to promote cross-contamination, might best be eliminated from the laundering procedure.

VII. EFFECTS OF LAUNDERING AIDS AND PRE-TREATMENT OF CLOTH

Use of Builders and CMC

Many commercial soaps and synthetic detergents contain so-called "builders" to enhance their cleansing action. Builders by themselves are of little or no value as detergents, but help to make detergents more effective by increasing the alkalinity of the solutions or by other less-well-understood modes of action. Sodium carbonate, sodium metasilicate, and the polyphosphates are among the most widely used builders.

Another widely publicized and apparently effective laundering aid is the sodium salt of carboxymethylcellulose, known as CMC. It is used to best advantage with anionic detergents, especially with soiled cotton goods, and the improved washing action is attributed to prevention of soil redeposition.^{12/}

To see whether such builders and cleaning aids used in combination with Rinso and Nacconol would improve the decontaminating ability of these detergents, some tests were made with Sr^{89} , Y^{91} , P^{32} , and I^{131} contaminated cloths. Proportions of the different agents used in the combinations were selected more or less at random, since studies in connection with conventional laundering applications have shown that optimum concentrations of builders vary widely with conditions of use. Results of the tests are given in Tables 16 through 19.

^{12/} Schwartz, A. M., and Perry, J. W., "Surface Active Agents," Interscience Publishers, New York, 1949, p. 379.

Table 16

REMOVAL OF SR⁸⁹ FROM COTTON CLOTH
BY DECONTAMINATING AGENTS USED SINGLY
AND IN COMBINATIONS

Test Conditions:

Duration of each wash and rinse: 5 minutes
Temp. of all solutions: 75° F.
Demineralized water used in all solutions and rinses
Level of contamination: Section A: 1700-2200 c/m/sample
Section B: 4000-5000

<u>Decontaminating Agents and Mixtures</u>	<u>Conc. of Each Agent, Percent</u>	<u>Cumulative Percent Removal</u>	
		<u>Wash & Rinse #1</u>	<u>Wash & Rinse #2</u>
<u>A. Agents Used Alone:</u>			
(1) Rinso	1.0	81.6	87.8
(2) Calgon	1.0	94.5	99.4
(3) Nacconol	1.0	80.6	89.9
<u>B. Agents Used in Combinations</u>			
(4) Rinso	1.0	95.9	98.3
Sodium Carbonate	1.0		
(5) Rinso	1.0	96.2	99.4
Calgon	1.0		
(6) Rinso	1.0	96.6	98.6
Sodium Metasilicate	1.0		
CMC	0.1		
(7) Nacconol	1.0	92.8	97.3
Sodium Metasilicate	1.0		
CMC	0.1		

Table 17

REMOVAL OF Y⁹¹ FROM COTTON CLOTH
BY DECONTAMINATING AGENTS USED SINGLY
AND IN COMBINATIONS

Test Conditions:

Duration of each wash and rinse: 5 minutes
Temp. of all solutions: 75° F.
Demineralized water used in all solutions and rinses
Level of contamination: Section A: 3700-5400 c/m/sample
Section B: 7000-8600

<u>Decontaminating Agents and Mixtures</u>	<u>Conc. of Each Agent, Percent</u>	<u>Cumulative Percent Removal</u>	
		<u>Wash & Rinse #1</u>	<u>Wash & Rinse #2</u>
<u>A. Agents Used Alone:</u>			
(1) Rinso	1.0	63.8	75.6
(2) Calgon	1.0	91.9	97.7
(3) Nacconol	1.0	66.0	79.0
<u>B. Agents Used in Combinations</u>			
(4) Rinso	1.0	78.4	85.8
Sodium Carbonate	1.0		
(5) Rinso	1.0	94.2	97.3
Calgon	1.0		
(6) Rinso	1.0	59.0	68.7
Sodium Metasilicate	1.0		
CMC	0.1		
(7) Nacconol	1.0	36.6	44.6
Sodium Metasilicate	1.0		
CMC	0.1		

Table 18

REMOVAL OF P³² FROM COTTON CLOTH
BY DECONTAMINATING AGENTS USED SINGLY
AND IN COMBINATIONS

Test Conditions:

Duration of each wash and rinse: 5 minutes
 Temp. of all solutions: 75° F.
 Demineralized water used in all solutions and rinses
 Level of contamination: Section A: 1000-2200 c/p/sample
 Section B: 4200-5200

<u>Decontaminating Agents and Mixtures</u>	<u>Conc. of Each Agent, Percent</u>	<u>Cumulative Percent Removal</u>	
		<u>Wash & Rinse #1</u>	<u>Wash & Rinse #2</u>
A. <u>Agents Used Alone:</u>			
(1) Rinso	1.0	89.3	92.0
(2) Calgon	1.0	78.2	85.4
(3) Nacconol	1.0	74.7	83.2
B. <u>Agents Used in Combinations:</u>			
(4) Rinso	1.0	83.1	90.4
Sodium Carbonate	1.0		
(5) Rinso	1.0	76.5	87.9
Calgon	1.0		
(6) Rinso	1.0	91.0	95.7
Sodium Metasilicate	1.0		
CMC	0.1		
(7) Nacconol	1.0	80.3	90.1
Sodium Metasilicate	1.0		
CMC	0.1		

Table 19

REMOVAL OF I¹³¹ FROM COTTON CLOTH
BY DECONTAMINATING AGENTS USED SINGLY
AND IN COMBINATIONS

Test Conditions:

Duration of each wash and rinse: 5 minutes
Temp. of all solutions: 75° F.
Demineralized water used in all solutions and rinses
Level of contamination: Section A: 2200-3000 c/m/sample
Section B: 1800-2600

<u>Decontaminating Agents and Mixtures</u>	<u>Conc. of Each Agent, Percent</u>	<u>Cumulative Percent Removal Wash & Rinse #1</u>	<u>Wash & Rinse #2</u>
A. <u>Agents Used Alone</u>			
(1) Rinso	1.0	94.0	96.6
(2) Calgon	1.0	97.6	98.6
(3) Nacconol	1.0	88.0	98.9
(4) Chlorox	1.0	95.7	98.1
B. <u>Agents Used in Combinations:</u>			
(5) Rinso	1.0	95.0	97.5
Sodium Carbonate	1.0		
(6) Rinso	1.0	87.2	88.3
Calgon	1.0		
(7) Rinso	1.0	94.5	97.0
Sodium Metasilicate	1.0		
CMC	0.1		
(8) Nacconol	1.0	94.5	97.4
Sodium Metasilicate	1.0		
CMC	0.1		
(9) Rinso alone, followed	0.3	89.8	93.1
by Chlorox alone	1.0	97.4	-

Rinso, when used alone with Sr^{89} , was not especially effective, and sodium carbonate was detrimental to removal of the isotope. When these two substances were used in combination, however, good results were obtained (98.3 per cent removal after two wash-rinse cycles). Similarly, Rinso-Calgon and Rinso-sodium metasilicate-CMC mixtures gave very satisfactory results, although Calgon was just as effective when used alone. Nacconol was also aided considerably by the addition of metasilicate and CMC.

In the Y^{91} tests, Rinso again gave better results when used together with sodium carbonate and with Calgon, but again removals were no better than with Calgon alone. In contrast to the results with Sr^{89} , however, the decontaminating efficiencies of both Rinso and Nacconol were decreased by the use of metasilicate and CMC. Thus it is evident that indiscriminate use of such aids may have adverse effects.

No really significant advantages or disadvantages resulted from the use of any of the aids with Rinso in the P^{32} experiments. Performance of Nacconol was improved slightly (to the extent of five to seven per cent) when used with sodium metasilicate and CMC, probably solely because of the resultant increase in pH.

Removals of I^{131} by Rinso and Nacconol were little affected by the presence of either carbonate or metasilicate plus CMC. An antagonistic effect was indicated, however, when Rinso and Calgon were used together. Removal efficiencies were some seven to 10

per cent greater when the agents were used individually. A supplementary test in which a Rinso wash was followed by a Chlorox treatment gave no significantly different results from those obtained when the agents were used separately.

Effect of Pre-Starching

Runs were made to see if cloth coated with a non-permanent type starch (Glosstex plastic starch, containing CMC) before contamination would be easier to decontaminate than plain cotton cloth. Using Sr^{89} and P^{32} , both starched and untreated samples were contaminated to the same level of activity, then subjected to washing with Nacconol, Rinso, and Versene, respectively.

Since the starch film is supposed to be removed during the laundering operation, it would be expected that activity deposited or adsorbed on this layer would be carried away with it into the bulk of the wash solution. This apparently occurs to some extent with the P^{32} , for decontamination did improve. From results with Sr^{89} , however, it appears as though strontium ions are able to combine with the cotton fibers despite the presence of the starch film, which either does not coat all of the fibers completely or is partially removed in the contaminating bath. Pre-starching actually proved to be more of a hindrance than an aid when detergents were used to remove Sr^{89} . Versene removed P^{32} and Sr^{89} about equally well from both treated and untreated samples. These results are depicted graphically in Figure 16.

FIG. 16 - EFFECT OF STARCHING
ON REMOVAL OF Sr^{89} AND
 P^{32} FROM COTTON CLOTH

KEY: U - UNTREATED CLOTH | - 1st WASH & RINSE
St - STARCHED CLOTH | - 2nd WASH & RINSE

Effect of Silicone Treatment

Cotton cloths previously treated with a silicone-containing solution to make them water repellent* were separately immersed in Sr^{89} , P^{32} , and I^{131} solutions. The treated samples were much less susceptible to contamination by Sr^{89} and slightly less susceptible to P^{32} , but retained considerably more of the I^{131} than did the untreated cloths. It is evident from this that reduction in wettability of a fabric and reducing the absorption of active solution do not necessarily retard contamination.

As shown by Figure 17, the decreased wettability of the silicone-treated fabric made decontamination by laundering methods generally more difficult. Even Versene, usually so effective against Sr^{89} , was only 97 per cent efficient in removing strontium from treated cloth as compared to 100 per cent with plain cloth. Removal of I^{131} was notably poorer in the case of the treated fabric. Since removal of this isotope seems to depend largely upon the dissolving and rinsing action of water itself, it might be expected that reduction in wettability would be especially important here. However, it could also be that the adsorptive forces binding the I^{131} to the silicone film coating the fibers are stronger and therefore more resistant to the desorbing action of the different agents. With P^{32} , results were much less marked,

* Samples of untreated and silicone-treated cotton cloth were furnished by the General Electric Co., Chemical Division, Chemical Materials Dept., Waterford, N.Y.

FIG. 17 -EFFECT OF SILICONE TREATMENT
ON REMOVAL OF Sr^{89} , P^{32} , AND I^{131} FROM COTTON CLOTH

although tap water removed very little of the contamination from the silicone-treated material.

Results of the field tests by the Army Quartermaster Corps ^{13/} are in accord with the above findings. They reported that water repellent finishes appear to pick up more contamination and to resist its removal to a greater degree than non-water-repellent materials.

Discussion of Results

It is indicated by the foregoing tests that excellent results can be obtained in decontamination laundering with soap and detergents if proper proportions of builders are used with them. The results appear to be somewhat specific, however, and the best mixture for use with one type of contamination may give adverse results with another. Several of the alkaline complexing agents, used alone, are at least as effective as the best mixtures that were formulated here. Of course, where soil removal is important as well as decontamination, use of a detergent simultaneously or in sequence with a complexing agent is indicated.

Pre-treatment of clothing with starch or silicone solution to facilitate subsequent decontamination does not appear to be worth the effort. In fact, removal of contamination is made more difficult by reducing the wettability of a fabric. Further work on susceptibility of various types of fibers to contamination and impregnation

^{13/} Steadman, Col. F. M., and Staff, op. cit., p. 1.

of fabrics may, however, eventually lead to the development and use of fabrics which can be more easily decontaminated and which are more resistant to both wet and dry contamination in the first place .

VIII. INVESTIGATION OF DRY CLEANING TECHNIQUES

As a means of reducing the volume of radioactive waste produced by laundering contaminated clothing, "dry cleaning" techniques were tested. Organic solvents were substituted for water as the bulk phase of the wash bath, while a small, immiscible aqueous phase was retained to wet and convey decontaminating agent to the cloth and to carry off radioactive substances removed from the cloth. Runs were made to determine extent of contamination of the solvent phase, percentage of moisture required, decontaminating efficiency of the agents found most effective in the laundering tests, and techniques producing minimum volumes of radioactive waste.

Removal of Sr^{89} by Two-Phase System

In tests with Sr^{89} contaminated cloth, it was found that in the absence of moisture the common dry cleaning solvents, Stoddard and 140 F solvent (petroleum fractions) and carbon tetrachloride, trichlorethylene, and perchlorethylene (chlorinated hydrocarbons), removed practically no contamination. However, when small amounts of water were added to the cleaning bath, some removal of Sr^{89} was noted. In fact, the higher percentage of moisture present, the greater the removal obtained, as shown by Table 20. Similar behavior was observed when lower and higher boiling solvents such as petroleum ether, acetone, kerosene, and xylene were tested.

Table 20

REMOVAL OF SR⁸⁹ FROM COTTON CLOTH
BY DRY CLEANING SOLVENTS

Test Conditions:

Average level of contamination: 2500 c/m/sample
Duration of cleaning: 15 minutes
Volume of solvent: 50 ml per sample

<u>Dry Cleaning Solvent</u>	<u>Percent Removal of Sr⁸⁹</u>
<u>A. Without moisture:</u>	
Stoddard Solvent	0 - 2.7
140 F Solvent	0 - 2.8
Carbon Tetrachloride	0
Trichlorethylene	1.3
Perchlorethylene	0 - 3.1
<u>B. Moisture added:</u>	
Stoddard Solvent plus	
0.1% H ₂ O	3.0
0.3% H ₂ O	4.9
0.9% H ₂ O	13.1
2.7% H ₂ O	18.9
8.1% H ₂ O	25.8

The addition of decontaminating agents to the aqueous phase resulted in very satisfactory removals of Sr^{89} . One per cent solutions of most of the same agents evaluated in the foregoing laundering tests were tried in a 10 per cent aqueous, 90 per cent Stoddard solvent system. Results of runs in which samples were subjected to two successive 15-minute cleanings followed by a five-minute rinse with water alone are presented in Figure 18. It is evident that Sr^{89} contamination can be removed as effectively by this modified dry cleaning process as by laundering with entirely aqueous wash solutions, provided efficient complexing agents are employed. Upon completion of the tests, the "laundry wastes" were allowed to stand for a time to permit separation. The Stoddard solvent, separated completely from the aqueous phase, was drawn off, monitored, and found to be essentially free of radioactivity and suitable for re-use.

The effects of varying both the volume and strength of the aqueous decontaminating portion of the cleaning system were studied next. Results of tests with Versene are shown graphically in Figure 19. Greater removals were obtained in the initial cleaning operation by increasing the volume of decontaminating solution present in the system. However, results obtained by two successive cleanings with five per cent or ten per cent aqueous systems were practically as good as those obtained with a 25 per

FIG.18-REMOVAL OF SR^{89} FROM COTTON CLOTH BY MODIFIED DRY CLEANING METHOD

DECONTAMINATING GENTS, 1% CONC. IN AQUEOUS PHASE

FIG. 19 - VARIATION IN REMOVAL OF Sr^{89}
WITH VOLUME & STRENGTH OF VERSENE SOLUTION

cent system. Even with a two per cent system, removals of up to 87 per cent resulted from two cleaning operations. The optimum concentration of Versene appeared to be one or two per cent by weight in the water phase. In tests with ammonium citrate, one per cent concentrations were also found to give the best results.

A series of runs were then made in which one per cent solutions of Versene in 10 per cent aqueous, 90 per cent Stoddard solvent systems were used for cleaning, and 10 per cent water, 90 per cent solvent mixtures were used for rinsing. As shown by Table 21, four to five successive cleaning operations resulted in essentially complete removal of Sr^{89} (Sequence A). On the other hand, a single cleaning with Versene followed by three rinsings gave practically the same results (Sequence D). Actually, there was little variation in the results obtained by any of the sequences tried. A final rinse using water alone (no solvent present) appears to have some merit, and since the amount of activity left on the cloth after a three-step cleaning procedure is so minute, this rinse could in all probability be disposed of directly as a non-active waste, leaving a minimum of radioactive waste to be evaporated.

Removal of Other Types of Contamination

Removal of Y^{91} , Ce^{141} , Fe^{59} , P^{32} , and I^{131} by the two-phase system was also investigated. Results obtained by subjecting cloths contaminated by these isotopes as well as by Sr^{89} to two cleanings with various agents and a rinse with water alone are summarized in

Table 21

EFFECTS OF VARIATION IN TECHNIQUE
ON SR⁸⁹ REMOVAL

Test Conditions:

Cleaning solution: Stoddard solvent 90%
aqueous phase 10%, by volume
Conc. of Versene in aqueous solution: 1% by weight
Duration of each cleaning and rinse: 10 minutes
Level of contamination: 4000-6000 c/m/sample

<u>Sequence of Operations</u>	<u>Cumulative Percent Removal of Sr⁸⁹</u>
A. Cleaning - 10% Versene sol'n	72.1
Cleaning - "	93.0
Cleaning - "	96.9
Cleaning - "	99.5
Cleaning - "	99.8
B. Cleaning - 10% Versene sol'n	79.6
Cleaning - "	95.5
Cleaning - "	98.8
Rinse - 100% water	99.2
C. Cleaning - 10% Versene sol'n	69.1
Cleaning - "	89.3
Rinse - 10% water	97.0
Rinse - 100% water	98.8
D. Cleaning - 10% Versene sol'n	82.4
Rinse - 10% water	94.4
Rinse - "	95.9
Rinse - 100 % water	99.5
E. Cleaning - 10% Versene sol'n	71.1
Rinse - 10% water	92.0
Rinse - "	96.4
Cleaning - 10% Versene sol'n	98.4

Table 22. The removals closely approximated those obtained with the same agents in the previous laundering tests. Calgon proved to be slightly more effective than either ammonium citrate or Versene in removing metallic contamination, while Versene was most effective against P^{32} and I^{131} . Soap, added to the cleaning bath in the form of an emulsion, was no more effective than water alone in ridding the cloth of water-soluble contaminants. In the case of I^{131} , the Stoddard solvent did not remain uncontaminated, but was responsible for removing some 28 to 33 per cent of the I^{131} originally present on the samples.

Effectiveness of the modified dry cleaning method in removing Sr^{89} and Fe^{59} dusts and precipitates was checked. Again results followed the same pattern as in the laundering tests, with Versene proving extremely effective against strontium, and Calgon against all forms of Fe^{59} contamination. Soap emulsion (0.5 per cent concentration in the aqueous phase) was far more efficient in removing both Sr^{89} and Fe^{59} dusts than in decontaminating cloths exposed to solutions of the same two isotopes. Variation in level of contamination from 2800 to 12,000 counts per minute per sample with carrier-free Sr^{89} solution was of little consequence, since percentage removals were roughly the same at both levels when ammonium citrate and Versene were used.

Discussion of Results

By the use of a two-phase system, a manifold reduction in volume of radioactive waste produced was accomplished. The activity was concentrated in the aqueous phase, which constituted only a fraction of the total volume of cleaning solution used.

Table 22

REMOVAL OF WATER-SOLUBLE CONTAMINATION FROM
COTTON BY MODIFIED DRY CLEANING METHOD

Test Conditions:

Laundry Cycle: Two 15 min. cleaning operations and
one 5 min. water rinse

Cleaning Solution: Stoddard solvent 90%, aqueous phase 10%,
by volume

Conc. of agents in aqueous phase: 1%, by weight

Level of contamination: 2500 c/m/sample, average

Two cloth samples per flask

<u>Decontaminant</u>	<u>Percent Removal</u>					
	<u>Sr⁸⁹</u>	<u>Y⁹¹</u>	<u>Ce¹⁴¹</u>	<u>Fe⁵⁹</u>	<u>P³²</u>	<u>I¹³¹</u>
(1) Ammonium Citrate	100	95.6	91.9	-	-	-
(2) Calgon	100	98.3	95.7	98.6	88.7*	78.8*
(3) CP Cleaner	100	-	-	-	96.2	83.6
(4) Soap Emulsion	-	73.7	-	-	91.4	-
(5) Versene (Reg.)	100	93.1	91.1	79.8**	97.3	85.5
(6) Water (Demin.) [†]	52.4	86.6	71.8	84.2	91.2	54.3

† Present in 10% by volume in cleaning solution.

* Calgonite substituted for Calgon.

** Versene Fe-3 Specific substituted for Versene (Regular).

Stoddard solvent, least expensive of the dry cleaning solvents, proved quite successful as a carrier for aqueous decontaminating solutions. Except in the case of I^{131} , it remained essentially free of contamination, separated easily and completely from the contaminated aqueous phase, and was re-used a number of times.

IX. SUMMARY

In this empirical study of clothing decontamination, the tests were performed on a laboratory scale to permit close control of the many variables involved and to afford some insight into the mechanisms of removal. Practical aspects were preserved as much as possible, however, by the use of a typical white cotton fabric, soiled by actual use in the laboratory, as the substrate for the decontamination tests.

General Findings: According to the results obtained, insoluble radioactive dusts mechanically occluded on the fabric can be satisfactorily removed by soap. However, in cases where water-soluble compounds of alkaline earths or heavy metals are deposited on the cloth, as a result of evaporation of active solution spilled or splashed on the clothing, soap tends to react with these substances and precipitate the metallic elements. The insoluble compounds thus formed adhere tenaciously to the fabric and tend to accumulate through repeated contamination-decontamination cycles. It would seem preferable, then, to use plain water in place of the soap solution to dissolve away the soluble deposits on the cloth, before proceeding with the cleaning operation. Here again complications arise, for the radioactive metallic ions liberated upon solution of the deposits tend to be adsorbed or enter into chemical combination at other uncontaminated sites, resulting in a certain amount of cross-contamination.

Therefore, suitable agents should be used along with water in the "break" to prevent this secondary contamination, and to remove metallic ions firmly attached to the cotton fibers as a result of the initial contamination.

Complexing agents are most effective in removing metallic ions strongly attached to the fibers, for they tend to form soluble metal complexes of such stability that the ions are "lifted" from the fabric and inactivated chemically. Whether the contaminants are present as ions, soluble salts, or precipitates is of little consequence if the agents used are specifically suited to the removal of the particular isotopes involved.

Anionic and non-ionic detergents are of considerably less value than the complexing agents in removing metallic ions. Builders and laundering aids enhance the action of detergents in some instances, but they should be used with discretion, for adverse as well as beneficial effects may be obtained. Combinations of detergents and complexing agents should give maximum soil removal along with radioisotope removal, and should be of special value when particulate matter and greasy soil are present. High wash bath temperatures are definitely advantageous when soaps are employed, but seem to be of little or no help when some synthetics are used. Detergents which liberate sodium ions in solution owe part of their effectiveness to cationic exchange, for when present in high concentration the sodium ions tend to replace the trace amounts of di- and tri-valent metals

held by the cotton fibers. Cationic sanitizing agents appear to have very limited applicability in decontamination.

Non-metallic isotopes are most readily desorbed from cotton by alkaline solutions. Results of tests with P^{32} suggest that hydroxyl ions, when present in sufficient number, are preferentially adsorbed and displace the negatively charged phosphate ions from the surface of the cloth. In the case of I^{131} , hot water alone is capable of removing the major portion of the contamination present on cotton cloth.

Variations in laundering technique can significantly affect the performance of some agents. As a general rule, wash bath temperatures of 170°F. or higher aid in the removal of radioisotopes. Very high concentrations (3 to 6 per cent) of complexing agents and anionic detergents afford maximum removal of metallic ions, but good results can also be obtained with considerably weaker (0.3 to 1 per cent) solutions of most of the complexing agents. Light loading of the washwheel promotes decontaminating efficiency, although duration of wash does not seem to be a critical factor. An effective decontaminating agent included in the "break" should minimize cross-contamination and permit the use of a short laundry procedure. Pre-treating cloth with a water-removable finish (starch) is of no particular help, and the application of a water-repellent finish (silicone) is detrimental to decontamination.

Substitution of water-immiscible organic solvents for water in the bulk phase of the wash bath does not detract from the decontami-

nating ability of the various agents. Since dry cloth tends to readily absorb moisture present in the solvent bath, intimate contact between the active ingredients in the aqueous phase and the contamination on the cloth is afforded, and only limited volumes of aqueous solution are actually required for decontamination. Sufficient water must be supplied in subsequent operations, however, to rinse away the contamination.

Practical Application: The choice of decontaminating agents and detergents to be used and the particular laundering procedures to be followed must, of course, depend upon the individual situation. Where waste disposal presents no real problem, adequate decontamination and cleaning of clothing at minimum cost and with minimum deterioration of the fabric should be of primary interest. The agents may then be selected according to their efficiency in removing the types of contamination encountered, and their cost, availability, and ease of handling.

To aid in the selection of these agents, Table 23 is presented, in which the various decontaminants and detergents investigated in this study are rated according to their ability to remove specific isotopes from cotton cloth under a given set of conditions. Indices of decontaminating efficiency assigned to the agents were calculated according to the following equation:

$$\text{Index of Decontaminating Efficiency} = 10 \times \frac{\% \text{ removed by agent} - \% \text{ removed by H}_2\text{O}}{100 - \% \text{ removed by H}_2\text{O}}$$

Table 23

RELATIVE EFFECTIVENESS OF VARIOUS AGENTS
IN REMOVING WATER-SOLUBLE CONTAMINATION

<u>Decontaminating</u> <u>Agent</u>	<u>Index of Decontaminating Efficiency</u>				
	<u>Sr⁸⁹</u>	<u>Y⁹¹</u>	<u>Ce¹⁴¹</u>	<u>Fe⁵⁹</u>	<u>P³²</u>
<u>Complexing Agents:</u>					
Ammonium Citrate	10	9	10	9	Neg.
Calgon	10	10	10	10	8*
Citric Acid	10	3	8	8	Neg.
Sodium Citrate	10	-	9	8	1
Versene (Reg.)	10	10	10	9**	8
<u>Detergents:</u>					
Du Rite	Neg.	-	-	4	3
Igepal CO	7	Neg.	6	4	3
Nacconol NR	9	6	6	5	1
Rinso	6	8	4	5	6
Roccal	9	3	Neg.	-	Neg.
<u>Gen'l Purpose Mixtures:</u>					
CP Cleaner	10	10	10	-	8
Radiacwash	10	-	-	-	7
Sodium Bicarbonate	4	8	7	-	5

* Calgonite substituted for Calgon.

** Versene Fe-3 Specific substituted for Versene (Regular).

This is the same method that was used in the Rochester study as a basis for comparing decontaminating agents. An index of 10 indicates maximum efficiency, while a negative index shows that water is more effective than the agent in question.

From a study of Table 23, it is evident that Calgon and Versene are of outstanding value in removing contaminants firmly bound to the cotton cloth by physicochemical forces. Commercially available mixtures containing these or chemically similar agents, such as CP Cleaner and Radiacwash, are likewise very effective. Any number of other combinations of complexing agents and detergents might be tried to obtain the best results possible. At Arco, Idaho, for instance, a combination of Versene T and Tide has proved successful in removing a wide range of contaminants.

Where radioactive laundry wastes are treated by biological oxidation processes, however, the choice of agents should be restricted to those which will not only give satisfactory removals, but which will also least inhibit biological activity. Wastes of very low pH, which result from the use of citric acid, are toxic to bacterial populations. Therefore, use of the more neutral ammonium or sodium salts of the acid as a source of the citrate ion is indicated. In cases where removals of specific isotopes can best be accomplished by citric acid because of the low pH, an alkaline agent used at one stage in the same laundering procedure would effect at least a partial neutralization of the resultant waste.

Versene, while very effective in decontamination, may tend to pass unchanged through a trickling filter, carrying complexed radioactive cations with it into the plant effluent. Calgon, on the other hand, might break down into meta- and ortho-phosphates, liberating the complexed radioactive ions and enabling them to be removed to a greater degree in the treatment process.

Excessively high concentrations of practically any of the surface active agents in the laundry waste would tend to cause sloughing of the zooglear slime growth present in trickling filters and foaming in activated sludge aeration tanks. Therefore, minimum concentrations of decontaminating agents should be used, and the results of this study indicate that satisfactory decontamination of clothing should be obtainable with solutions of considerably less than the six per cent strengths specified in some procedures. Dilution by the use of multiple water rinses in the laundering procedures or the admixture of the laundry wastes with sanitary sewage would of course tend to alleviate treatment problems due to highly concentrated wastes. Where detergents are used along with complexing agents, soap might be tried in place of synthetic detergents, since it is not only effective against insoluble contaminants but also generally more amenable to treatment than many types of synthetics.

At installations where laundry wastes are evaporated or stored, the volume of waste produced is of utmost importance economically. Therefore, procedures involving a minimum number of washing and rinsing

operations should certainly be tried here. Even in commercial laundering, three-step procedures (break, suds, cooling rinse) have been used, in contrast to the eight or more step washing formulas recommended by the American Institute of Laundering, and with reportedly satisfactory results in removing soil.^{14/} In any event, the employment of effective agents in the initial steps of the laundering operation should conceivably remove such a large proportion of any contamination present that only the wastes resulting from the first two or perhaps three steps need be treated as "hot" wastes. Subsequent washes and/or rinses could then be disposed of more economically as non-active wastes, although temporary storage to permit monitoring might be advisable as a precautionary measure.

The application of "dry cleaning" techniques to the decontamination of cotton clothing should reduce the volume of radioactive waste produced to an absolute minimum. Reclamation and re-use of the major portion of the cleaning bath, the organic solvent, should prove feasible under actual operating conditions, just as in commercial dry cleaning. The costs involved in changing over from conventional laundering methods and in operating such a system would, however, have to be investigated and balanced against the savings that would result from a reduction in the volume of active waste that has to be stored or processed.

^{14/} American Institute of Laundering, "Washing and Finishing Methods at the Modern Way Laundry", Special Report No. 176, Joliet, Ill., Feb. 1949.

APPENDIX

Table A-1

EFFECT OF DRYING OF CLOTH AFTER EACH
LAUNDERING OPERATION ON REMOVAL EFFICIENCY

Laundry cycle used: 10 min. wash, 5 min. rinse,
10 min. wash, and 5 min. rinse

Decontaminating agent: Versene, 3% solution, first wash;
1% solution, second wash

Level of contamination: Sr⁸⁹: 3200-5000 c/m/sample
Ce¹⁴¹: 11,000-17,000 c/m/sample

<u>Treatment of Sample</u>	<u>Cumulative Percent Removal</u>			
	<u>Wash #1</u>	<u>Rinse #1</u>	<u>Wash #2</u>	<u>Rinse #2</u>
A. <u>Strontium 89:</u>				
(1) Dried and counted after each operation	94.6	99.7	100	100
(2) Dried and counted after each wash-rinse <u>cycle</u>	*	100	*	100
(3) Dried and counted only <u>after final rinse</u>	*	*	*	100
B. <u>Cerium 141:</u>				
(1) Dried and counted after each operation	92.3	97.8	89.9	99.1
(2) Dried and counted after each wash-rinse <u>cycle</u>	*	97.5	*	98.6
(3) Dried and counted only <u>after final rinse</u>	*	*	*	98.5

APPENDIX

TABLE A-2 VARIABILITY IN PERCENTAGE REMOVAL
OF SR⁸⁹ FROM COTTON CLOTH
BY LAUNDERING

A. Versene Wash

<u>Sample</u> <u>Number</u>	<u>Original</u> <u>Count</u>	<u>Count</u> <u>after</u> <u>1st</u> <u>Wash</u>	<u>Percent</u> <u>Removal</u>	<u>Count</u> <u>after</u> <u>2nd</u> <u>Wash</u>	<u>Cumulative</u> <u>Percent</u> <u>Removal</u>	<u>Count</u> <u>after</u> <u>1st</u> <u>Rinse</u>	<u>Cumulative</u> <u>Percent</u> <u>Removal</u>
1	2198	150	93.2	8	99.5	0	100.0
2	2464	132	94.6	9	99.5	0	100.0
3	1894	194	89.8	3	99.8	0	100.0
4	2674	137	94.7	7	99.9	0	100.0
5	2404	148	93.7	12	99.3	0	100.0
6	2674	136	95.0	12	99.6	0	100.0
7	2229	170	92.3	7	99.8	0	100.0
8	2292	151	93.5	2	99.9	0	100.0
9	2826	175	93.8	3	99.9	0	100.0
10	2539	194	92.4	5	99.7	0	100.0
Arith. Mean			94.6		99.7		100.0
Std. Dev.			1.95		0.20		0
Prob. Error of Mean			0.41		0.04		0

APPENDIX

TABLE A-2 (cont.)

B. Nacconol NR Wash

<u>Sample Number</u>	<u>Original Count</u>	<u>Count after 1st Wash</u>	<u>Percent Removal</u>	<u>Count after 2nd Wash</u>	<u>Cumulative Percent Removal</u>	<u>Count after 1st Rinse</u>	<u>Cumulative Percent Removal</u>
1	2009	1270	38.6	806	59.8	419	79.2
2	1683	709	57.9	519	69.2	451	73.2
3	2141	1323	38.2	999	53.3	825	61.4
4	2938	2368	19.4	1969	33.0	1632	44.4
5	1687	699	58.6	528	68.7	406	76.0
6	2436	1387	43.1	1043	57.3	903	63.0
7	3137	2612	16.8	2226	29.1	1958	37.6
8	2872	1958	31.8	1714	40.3	1256	56.3
9	2481	1401	43.5	427	82.6	347	85.9
10	2208	1346	39.0	288	86.9	119	94.5
Arith. Mean			38.5		58.0		67.2
Std. Dev.			13.1		18.7		17.1
Prob. Error of Mean			2.8		4.0		3.7

APPENDIX

Table A-3

REMOVAL OF RADIOISOTOPES FROM COTTON CLOTH
BY VARYING CONCENTRATIONS OF DECONTAMINATING AGENTS

Test Conditions:

Ave. Level of Contamination: 200 c/m/sample
Temp. of Solutions: 72-75° F.
Rinse Solution: Demineralized Water
No. of Cloth Samples per Flask: 1
Volume of Solution per Sample: 50 ml
Duration of Wash: 10 minutes
Duration of Rinse: 5 minutes
All tests run in duplicate; average results reported

<u>Decontaminating Agent</u>	<u>Conc., Per Cent</u>	<u>Cumulative Percent Removal</u>			
		<u>Wash #1</u>	<u>Rinse #1</u>	<u>Wash #2</u>	<u>Rinse #2</u>
<u>A.. Strontium 89:</u>					
(1) Ammonium Citrate	0.3	92.2	94.8	100	100
	1.0	93.7	98.5	100	100
	3.0	95.2	99.7	100	100
(2) Calgon	0.3	88.5	89.5	98.6	98.8
	1.0	91.8	94.5	98.9	99.4
	3.0	93.3	97.9	99.5	99.9
(3) Citric Acid	0.3	81.0	92.2	96.1	97.0
	1.0	84.1	90.5	96.8	97.8
	3.0	86.1	95.3	99.2	99.2
	6.0	88.5	96.9	99.9	99.9
(4) CP Cleaner	0.3	91.3	9.29	98.9	99.4
	1.0	93.1	98.7	99.5	99.7
	3.0	94.8	99.4	99.8	100
(5) Demineralized Water	-	55.3	63.3	66.0	72.4
(6) Du Rite	0.3	44.2	44.9	52.5	53.2
	1.0	25.1	22.0	31.7	32.3
	3.0	75.6	62.3	62.5	62.6
	6.0	88.3	96.2	96.2	98.5
(7) Igepal	0.3	59.5	75.9	79.4	88.6
	1.0	65.6	76.6	85.1	86.7
	3.0	64.0	78.8	87.1	91.0
	6.0	32.6	42.2	60.0	72.3

APPENDIX

Table A-3 (cont.)

Decontaminating Agent	Conc., Per Cent	Cumulative Percent Removal			
		Wash #1	Rinse #1	Wash #2	Rinse #2
A. Strontium 89:					
(8) Nacconol	0.3	70.4	73.3	87.8	88.0
	1.0	77.2	80.6	88.5	89.9
	3.0	77.6	85.0	92.0	98.7
	6.0	93.8	96.6	97.9	99.6
(9) Radiacwash	0.3	74.7	76.1	97.1	97.1
	1.0	93.8	95.8	99.4	99.4
	3.0	94.4	99.5	99.5	99.5
(10) Rinso	0.3	67.4	74.2	82.0	84.0
	1.0	70.4	81.6	86.7	87.8
	3.0	71.9	81.0	85.5	87.7
(11) Sodium Citrate	0.3	89.9	92.1	98.9	99.2
	1.0	92.9	95.1	99.1	99.4
	3.0	94.1	98.3	99.8	99.8
(12) Tap Water	-	58.7	84.5	94.4	98.3
(13) Versene	0.3	94.0	99.7	100	100
	1.0	94.4	100	100	100
	3.0	95.1	99.7	100	100
B. Yttrium 91:					
(1) Ammonium Citrate	0.3	78.7	88.1	90.8	91.3
	1.0	83.5	91.2	94.6	95.3
	3.0	89.1	96.4	97.7	98.3
(2) Calgon	0.3	82.4	93.4	97.0	97.0
	1.0	83.1	91.9	97.7	97.7
	3.0	85.7	98.7	99.2	99.7
(3) Citric Acid	0.3	29.4	38.6	62.5	65.4
	1.0	28.8	36.1	50.4	51.6
	3.0	45.8	49.3	58.8	62.0
(4) CP Cleaner	0.3	81.0	93.9	97.1	97.8
	1.0	90.0	97.4	98.9	99.3
	3.0	87.0	98.2	99.1	99.4

APPENDIX

Table A-3 (cont.)

Decontaminating Agent	Conc., Per Cent	Cumulative Percent Removal			
		Wash #1	Rinse #1	Wash #2	Rinse #2
B. Yttrium 91:					
(5) Demineralized Water	-	13.6	32.2	36.9	44.1
(6) Igepal	0.3	21.3	27.2	31.6	32.9
	1.0	16.8	22.5	22.6	26.9
	3.0	13.7	21.1	25.1	25.7
	6.0	16.0	19.7	23.4	26.7
(7) Nacconol	0.3	46.2	52.5	63.0	64.1
	1.0	57.1	66.0	73.5	79.0
	3.0	59.5	63.2	72.7	78.1
(8) Rinso	0.3	34.7	48.5	52.0	56.0
	1.0	49.9	63.8	68.1	75.6
	3.0	70.2	81.7	86.5	87.5
(9) Tap Water	-	13.8	24.1	25.9	33.8
(10) Versene	0.3	76.7	90.9	96.8	97.1
	1.0	88.3	94.7	97.5	98.2
	3.0	87.6	98.9	99.2	99.4
C. Iron 59:					
(1) Ammonium Citrate	0.3	96.7	79.1	86.6	88.3
	1.0	79.9	93.6	96.8	96.9
	3.0	83.4	93.9	96.9	97.6
(2) Calgon	0.3	78.6	89.7	91.2	94.0
	1.0	85.9	92.2	96.8	97.5
	3.0	90.0	96.6	98.1	98.7
(3) Citric Acid	0.3	71.2	88.5	89.0	92.1
	1.0	69.9	80.1	88.6	92.1
	3.0	79.2	86.9	91.2	93.0
(4) Demineralized Water	-	37.8	52.1	57.2	63.4
(5) Du Rite	0.3	23.3	27.0	40.6	42.0
	1.0	34.8	40.2	59.1	62.6
	3.0	63.1	66.5	79.3	79.5

APPENDIX

Table A-3 (cont.)

Decontaminating Agent	Conc., Per Cent	Cumulative Percent Removal			
		Wash #1	Rinse #1	Wash #2	Rinse #2
C. Iron 59:					
(6) Igepal	0.3	61.7	66.8	77.5	82.1
	1.0	52.2	61.6	66.3	68.8
	3.0	49.5	63.6	74.7	78.7
(7) Nacconol	0.3	50.5	60.7	65.0	67.0
	1.0	58.4	64.9	69.0	74.3
	3.0	61.4	74.5	79.0	81.5
(8) Rinso	0.3	54.4	65.4	68.8	71.7
	1.0	54.5	61.2	66.0	66.1
	3.0	67.5	75.7	79.1	80.3
(9) Sodium Citrate	0.3	69.3	79.6	83.3	85.8
	1.0	72.7	82.4	88.1	93.5
	3.0	82.0	91.2	94.5	94.8
(10) Versene (Reg.)	0.3	81.3	86.7	90.0	91.4
	1.0	71.5	78.7	82.8	84.1
	3.0	50.3	78.7	83.3	85.9
D. Phosphorus 32:					
(1) Ammonium Citrate	0.3	51.7	53.5	69.4	73.3
	1.0	62.0	69.5	73.6	74.7
	3.0	66.7	75.0	78.6	81.0
	6.0	45.1	59.1	68.5	72.0
(2) Calgon	0.3	71.2	81.0	84.5	85.8
	1.0	73.7	78.2	84.2	85.4
	3.0	68.5	77.5	80.0	80.4
(3) Citric Acid	0.3	36.8	42.8	44.9	49.1
	1.0	37.9	40.8	47.5	47.5
	3.0	42.6	45.5	52.5	53.2
	6.0	40.0	46.5	53.6	57.7
(4) CP Cleaner	0.3	87.3	93.4	95.2	95.3
	1.0	89.1	94.0	95.8	96.1
	3.0	87.2	92.1	94.1	95.0
(5) Demineralized Water	-	65.6	75.4	78.8	81.9

APPENDIX

Table A-3 (cont.)

Decontaminating Agent	Conc., Per Cent	Cumulative Percent Removal			
		Wash #1	Rinse #1	Wash #2	Rinse #2
<u>D. Phosphorus 32:</u>					
(6) Du Rite	0.3	62.5	69.1	75.8	79.7
	1.0	72.7	79.2	84.8	87.0
	3.0	76.3	84.4	88.6	89.2
	6.0	66.6	83.0	87.1	88.1
(7) Igepal	0.3	64.8	76.0	78.2	79.9
	1.0	60.0	69.7	72.5	74.6
	3.0	62.5	70.6	74.2	76.2
(8) Nacconol	0.3	63.2	73.0	81.4	81.5
	1.0	65.0	74.7	81.7	83.2
	3.0	68.3	72.8	78.0	82.2
(9) Radiacwash	0.3	82.5	90.2	92.5	93.4
	1.0	86.7	92.1	94.3	94.3
	3.0	89.0	94.0	95.8	95.8
(10) Rinso	0.3	78.8	87.8	90.3	91.4
	1.0	81.0	89.3	91.2	92.0
	3.0	80.5	88.3	90.0	90.8
(11) Sodium Citrate	0.3	72.2	82.5	85.2	87.7
	1.0	57.0	73.7	77.9	84.0
	3.0	64.5	75.9	77.8	80.5
(12) Tap Water	-	67.0	76.5	80.6	81.3
(13) Versene	0.3	89.7	95.0	95.8	95.8
	1.0	87.6	93.0	94.8	96.2
	3.0	87.7	92.5	93.9	94.5
<u>E. Iodine 131:</u>					
(1) Ammonium Citrate	0.3	81.6	88.6	91.8	93.1
	1.0	84.9	93.1	95.4	96.2
	3.0	83.9	92.1	93.8	95.2
(2) Calgon	0.3	93.9	97.8	98.5	99.1
	1.0	94.8	97.6	98.0	98.6
	3.0	92.5	97.7	98.5	98.5

APPENDIX

Table A-3 (cont.)

Decontaminating Agent	Conc., Per Cent	Cumulative Percent Removal			
		Wash #1	Rinse #1	Wash #2	Rinse #2
<u>E. Iodine 131:</u>					
(3) Chlorox	0.3	87.2	95.9	97.1	97.7
	1.0	87.7	95.7	97.3	98.1
	3.0	90.6	98.1	98.4	99.3
(4) Citric Acid	0.3	63.9	74.9	80.6	82.9
	1.0	70.4	78.3	84.9	95.0
	3.0	70.1	79.8	83.0	95.2
(5) CP Cleaner	0.3	86.4	93.5	94.6	95.6
	1.0	88.6	95.7	96.6	96.2
	3.0	87.1	94.9	95.8	96.8
(6) Demineralized Water	-	86.4	87.4	94.0	95.2
(7) Du Rite	0.3	84.6	92.2	94.1	95.5
	1.0	86.5	93.9	95.7	96.0
	3.0	84.7	93.1	94.7	95.6
(8) Igepal	0.3	90.6	94.5	96.5	97.3
	1.0	88.7	94.7	96.7	96.7
	3.0	88.6	95.1	96.8	96.8
(9) Nacconol	0.3	91.2	96.0	98.1	98.1
	1.0	86.0	88.0	91.4	98.9
	3.0	89.6	94.4	97.3	97.5
(10) Potassium Iodide	0.3	91.1	97.3	98.0	98.4
	1.0	91.2	98.2	98.5	99.0
	3.0	92.6	98.2	99.1	99.2
(11) Radiacwash	0.3	87.6	93.4	95.1	96.4
	1.0	85.3	92.6	94.5	95.1
	3.0	86.1	91.9	94.5	95.1
(12) Rinso	0.3	73.3	74.5	93.9	95.5
	1.0	82.3	94.0	94.7	96.6
	3.0	83.0	94.4	95.7	97.2
(13) Sodium Citrate	0.3	92.5	98.0	98.5	98.5
	1.0	92.8	96.7	98.4	99.0
	3.0	92.1	98.1	98.8	98.8

APPENDIX

Table A-3 (cont.)

<u>Decontaminating Agent</u>	<u>Conc., Per Cent</u>	<u>Cumulative Percent Removal</u>			
		<u>Wash #1</u>	<u>Rinse #1</u>	<u>Wash #2</u>	<u>Rinse #2</u>
<u>E. Iodine 131:</u>					
(14) Tap Water	-	85.4	90.8	91.4	93.1
(15) Versene	0.3	74.1	87.5	90.5	91.9
	1.0	81.5	89.7	92.1	95.2
	3.0	73.6	88.2	90.8	92.7