U.S. Department of Commerce National Bureau of Standards

RESEARCH PAPER RP711

Part of Journal of Research of the National Bureau of Standards, Volume 13, September 1934

PROPERTIES OF KNIT UNDERWEAR FABRICS OF VARIOUS CONSTRUCTIONS

By Charles H. Hamlin[1] and Ruby K. Worner

ABSTRACT

Knit underwear is made in a variety of weights, thicknesses, and constructions from cotton, wool, silk, rayon, and combinations of these fibers. Yet comprehensive data on the properties of underwear fabrics have not been available. The purpose of this paper is to supply data on representative underwear fabrics relative to the properties that appear to be important from the standpoint of comfort and health.

The thermal transmission, air permeability, thickness, weight, compressional characteristics, and coefficient of friction, measured under specified conditions, are recorded for 97 representative fabrics of given constructions and fiber compositions.

The interrelations between properties are shown graphically with the constructions and fiber compositions of the individual fabrics indicated. In general, the thermal transmission and air permeability of these fabrics varied inversely with thickness and with weight, the total compression varied directly with thickness, and the compressibility varied directly with density. The coefficient of friction was lowest for fabrics made from continuous filament silk and rayon yarns. It is evident, however, that when any one property is fixed, the other properties may be varied considerably.

CONTENTS

I. INTRODUCTION

The purpose of this paper is to record the results of measurements of thermal transmission, air permeability, thickness, weight, compressional characteristics, and coefficient of friction for a large variety of new unlaundered underwear fabrics under certain specified conditions. The fiber composition and details of construction of the fabrics are recorded and the interrelations between properties are shown graphically with the construction and fiber composition of the individual fabrics indicated. These measurements provide a line of attack on the problem of developing underwear with optimum properties as regards comfort and health.

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This work was started several years ago as a cooperative study between the Underwear Institute (then the Associated Knit Underwear Manufacturers of America) and the National Bureau of Standards. The generous cooperation of the manufacturers who furnished the fabrics is gratefully acknowledged. The assistance of William D. Appel and H. F. Schiefer in the preparation of this paper is appreciated.

II. THE FABRICS

Ninety-seven underwear fabrics were examined. All of them were in commercial use for the manufacture of undergarments when the study was started. Ninety-four were of knit construction, 11 of them 2-layer fabrics, and 3 were of woven construction. The details of construction of the fabrics are given in table 1, in which the fabrics are arranged in the order of increasing thickness. The fabrics of the same thickness are listed in the order of increasing weight. Fabrics made from cotton; rayon; silk; wool; cotton and wool; rayon and silk; rayon and wool; silk and wool; cotton, rayon, and wool; and cotton, silk, and wool were included. Five types of knitting were represented; namely, plain (sometimes designated "circular flat knit"); rib; Rubenstein[2]; warp; and mesh. These constructions are illustrated in figures 1 (A to I).

[2] Edwin D. Fowle, *What is the Rubenstein Patent?* Textile World 78, 2814,(Dec. 13, 1930). See also U.S. Patent no. 1755968.

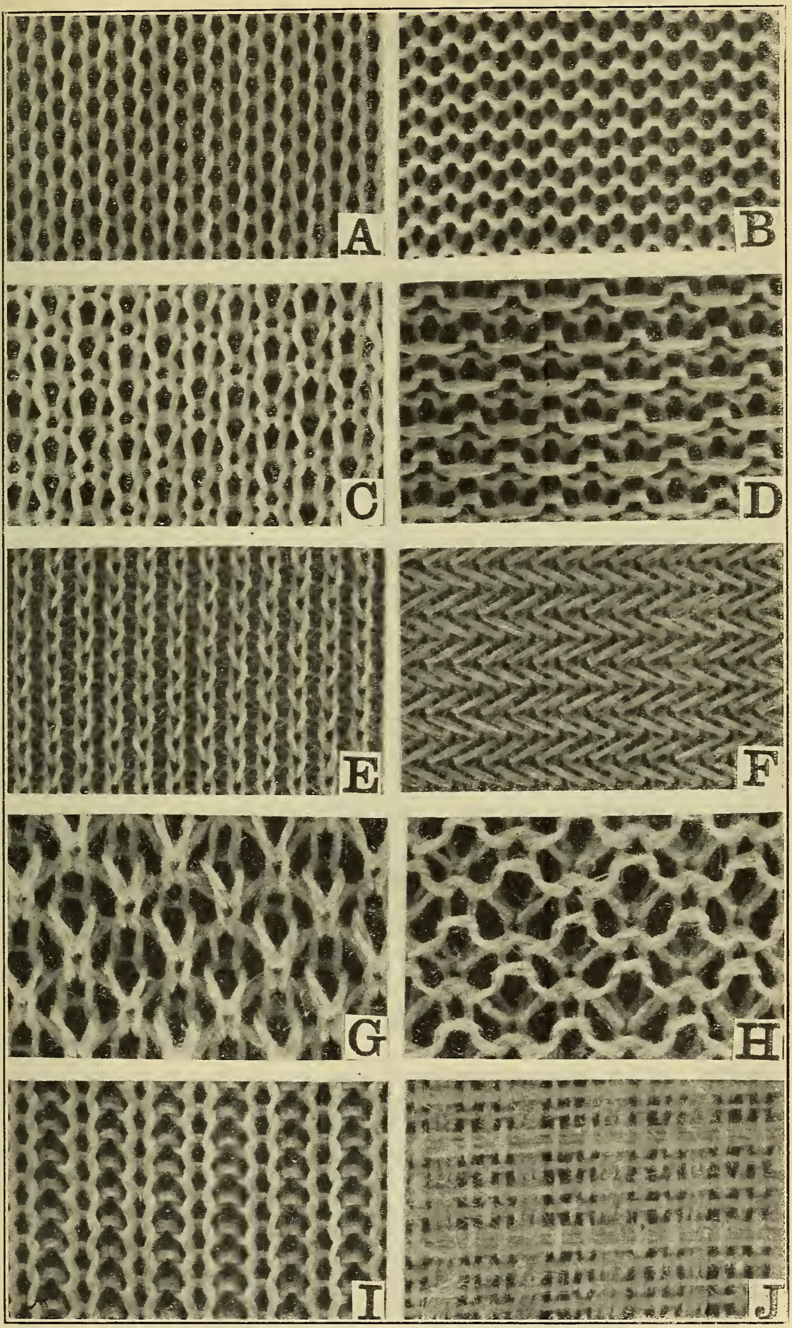

FIGURE 1.—*Types of interlacing.*

A. Plain knit, face.
B. Plain knit, back.
C. Rubenstein knit, face.
D. Rubenstein knit, back.
E. Warp knit, face.
F. Warp knit, back.
G. Mesh knit, face.
H. Mesh knit, back.
I. Rib knit, face, and back.
J. Woven, face, and back.

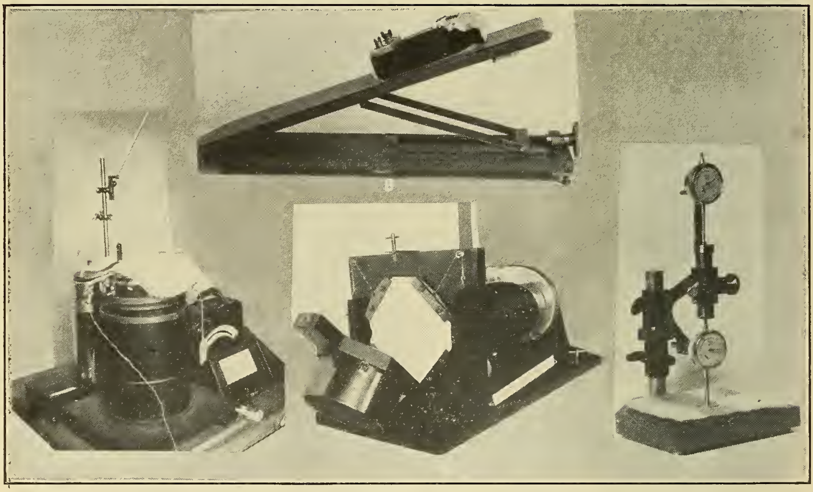

FIGURE 2.—*Equipment used for testing underwear fabrics for:*

A, Thermal transmission; *B*, air permeability; *C*, compressional characteristics; *D*, coefficient of friction.

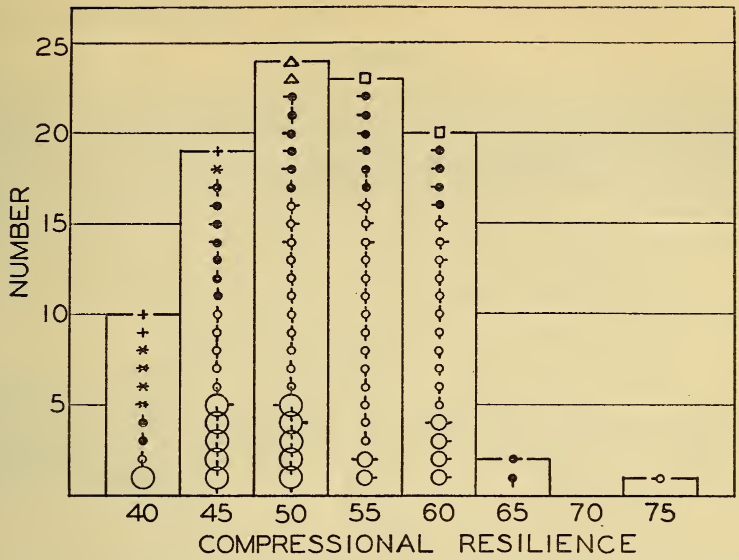

FIGURE 3.—*Distribution of fabrics with respect to compressional resilience (percent).*

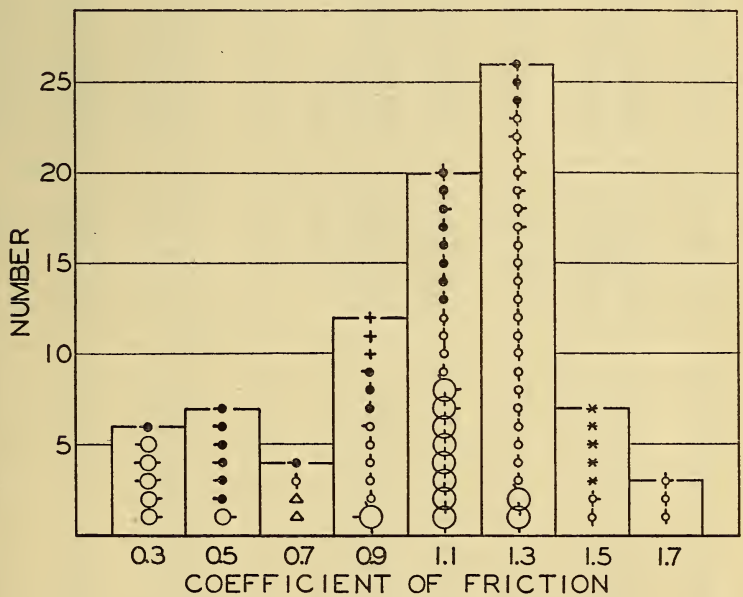

FIGURE 4.—*Distribution of fabrics with respect to coefficient of friction.*

TABLE 1.—*Details of construction and*

NOTES

Column

5 *Thermal transmission.*—Quantity of heat lost through the fabric when in contact on one side with a horizontal hot plate and on the other with still air, expressed in British thermal units per hour per square foot of fabric per degree Fahrenheit difference in temperature between the hot plate and the air above the fabric.

6 *Air permeability.*—Number of cubic feet of air perminute passing through 1 square foot of fabric, at a pressure drop across the fabric of 0.3 inches of water.

7 *Total compression.*—The change in thickness when the pressure is increased from 0.1 to 2.0 pounds per square inch.

1	2	3	4	5	6	7	8	9	10	11	12
Sample no.	Standard thickness	Weight	Density	Thermal transmission	Air permeability	Total compression	Compressibility	Compressional resilience	Coefficient of friction	Fiber: C=cotton, R=rayon, S=silk, s=spun, W=wool, w=weighted, numerals=contents %	Interlacing: f=fleeced, m=mesh knit, p=plain knit, r=rib knit, R=Rubenstein knit, w=warp knit
	In.	*Oz/yd²*	*Lb/ft³*			*In.*	*In²/lb*	*Percent*			
1	0.009	1.42	13.1	2.03	427	0.0030	0.13	58	0.4	S	w
2	.009	1.52	14.1	1.70	388	.0025	.13	57	.5	S	w
3	.010	2.06	17.2	1.91	517	.0025	.11	62	.3	Sw	w
4	.011	2.64	20.0	1.51	392	.0020	.08	62	.3	88R, 12S	w
5	.011	2.65	20.1	1.84	649	.0015	.05	60	.4	R	p
6	.011	2.65	20.1	1.62	586	.0015	.06	56	.5	R	p
7	.011	2.69	20.4	1.62	513	.0020	.08	54		R	p
8	.012	2.39	16.6	1.54	453	.0025	.07	55	.2	85R, 15S	w
9	.012	2.89	20.1	1.88	547	.0015	.05	49	.4	R	p
10	.012	2.92	20.3	1.85	663	.0016	.06	46	.4	R	p
11	.012	2.97	20.6	2.17	152	.0030	.11	41	.9	C	woven
12	.013	3.77	24.2	2.07	489	.0020	.05	47		R	p
13	.013	3.81	24.4	2.00	425	.0025	.08	53		R	p
14	.014	3.00	17.9	1.42	455	.0020	.06	62	.4	R	w
15	.014	3.39	20.2		671	.0015	.05	59		R	p
16	.014	3.63	21.6	2.35	557	.0015	.05	59	.4	R	p
17	.014	3.87	23.0	1.67	491	.0015	.04	52	.5	R	p
18	.015	3.29	18.3		635	.0020	.06	55		R	p
19	.015	3.49	19.4	1.84	152	.0040	.10	46	1.0	C	woven
20	.016	2.98	15.5	1.45	451	.0055	.14	49	.7	Rs	p
21	.016	3.61	18.8	1.73	668	.0030	.10	60		R	R
22	.016	4.02	20.9	1.99	537	.0020	.06	62	.5	R	p
23	.017	3.11	15.2	1.34	269	.0050	.11	67	1.1	Ss	p
24	.017	3.13	15.3	1.51	451	.0050	.11	55	1.0	Rs	p
25	.017	3.40	16.7	1.47	284	.0040	.10	48	1.1	C	p
26	.017	3.95	19.4		593	.0040	.12	53		R	R
27	.018	3.08	14.3	1.41	339	.0075	.14	47	1.1	C	p
28	.019	2.86	12.5	1.48	465	.0100	.19	66	1.2	W	p
29	.019	3.66	16.1	1.73	258	.0060	.11	42	1.0	C	p
30	.020	3.72	15.5	1.73	237	.0065	.12	41	1.1	C	p
31	.021	3.16	12.5	1.98	347	.0075	.14	44	.8	C	p
32	.022	2.77	10.5	1.70	550	.0100	.20	49	.8	C	m
33	.022	3.28	12.4	1.59	414	.0085	.15	49	.6	C	m
34	.022	3.53	13.4	1.46	319	.0085	.13	45	1.2	C	p
35	.023	3.13	11.3	1.56	524	.0105	.20	56	.8	C	p
36	.023	5.64	20.4	1.71	196	.0075	.11	46	1.1	32C, 37R, 31W.	p
37	.025	5.20	17.3	1.64	228	.0090	.14	52	1.2	29R, 71W	p
38	.026	4.00	12.8	1.56	319	.0070	.12	56	.9	C	r
39	.026	4.22	13.5	1.48	224	.0060	.10	53	1.0	C	r
40	.026	4.63	14.8	1.62	316	.0065	.10	61	1.3	C	r

properties of underwear fabrics

NOTES—Continued

Column

8 *Compressibility.*—The ratio of the decrement in thickness to the increment in pressure for unit thickness at a pressure of 1 pound per square inch.

9 *Compressional resiliance.*—The amount of work recovered from the specimen when the pressure is decreased from 2 to 0.1 pound per square inch, expressed as a percentage of the work done on the specimen when the pressure is increased from 0.1 to 2 pounds per square inch.

10 *Coefficient of friction.*—The tangent of the limiting angle between the inclined plane and the horizontal. See test procedure.

16 *Yarn number* (TYPP).—Number of thousand yarns per pound.

13	14	15	16	17		18
Finish: b=bleached, d=dyed, dr=dyed random, g=grey, m=mercerized	Wales or warp yarns per inch	Courses or filling yarns per inch	Yarn number (TYPP): C=cotton, CW=cotton and wool mixed, f=filling, R=rayon, S=silk, W=wool, w=warp	Twist—turns per inch: C=cotton, CW=cotton and wool mixed, f=filling, R=rayon, S=silk, w=warp, W=wool		Notes
				Single	Plied	
d	48	63	------	------	------	
d	46	64	------	------	------	
d	53	66	------	------	------	
d	42	55	------	------	------	
d	46	49	43.0	3	------	
d	46	49	41.5	4	------	
d	52	47	44.5	6	------	
d	44	57	------	------	------	
d	46	52	42.5	4	------	
d	47	52	42.5	4	------	
b	80	75	28.0w, 34.5f.	21w, 19f	------	
b	48	50	41.5	3	------	
d	39	48	30.0	6	------	
d	46	52	------	------	------	
d	38	43	29.0	3	------	
b	44	44	30.5	2	------	
d	43	46	28.5	4	------	
d	37	46	29.0	3	------	
g	80	75	28.0w, 34.5f	21w, 19f	------	
b	35	35	28.5	19	------	
d	38	42	28.5	3	------	
d	45	45	28.5	3	------	
b	39	36	30.0	8	------	
b	34	38	28.5	19	------	
bm	35	41	28.5	22	17	2-ply yarns.
d	41	37	29.0	3	------	
b	36	35	31.0	18	------	
b	37	35	31.5	20	------	
b	35	41	25.0	18	------	
b	34	43	25.5	19	------	
b	26	25	18.0	14	------	
bm	30	28	31.0	31	15	2-ply yarns.
b	32	22	30.5	20	------	
b	26	33	19.5	16	------	
g	25	26	18.0	14	------	
b	31	38	16.5	17CW, 3R	------	Single rayon and single cotton-and-wool yarn knit as 1 in each course.
b	35	36	18.5	13W, 4R	------	Single worsted and single rayon yarn knit as 1 in each course.
b	28	29	31.0	19	------	
b	28	29	27.5	18	------	
bm	29	32	27.5	22	16	2-ply yarns.

TABLE 1.—*Details of construction and*

1	2	3	4	5	6	7	8	9	10	11	12
Sample no.	Standard thickness	Weight	Density	Thermal transmission	Air permeability	Total compression	Compressibility	Compressional resilience	Coefficient of friction	Fiber: C=cotton, R=rayon, S=silk, s=spun, W=wool, w=weighted, numerals=contents %	Interlacing: f=fleeced, m=mesh knit, p=plain knit, r=rib knit, R=Rubenstein knit, w=warp knit
	In.	*Oz/yd²*	*Lb/ft³*			*In.*	*In.²/lb*	*Percent*			
41	.026	5.21	16.7	1.56	750	.0040	.05	73	.9	R	r
42	.027	4.65	14.4	1.73	203	.0080	.11	52	1.2	C	r
43	.027	5.45	16.8	1.40	157	.0080	.12	49	1.2	71C, 29W	p
44	.028	5.78	17.2	1.23	192	.0130	.16	54	1.2	W	p
45	.030	4.36	12.1	1.28	240	.0070	.09	46	1.0	C	r
46	.034	5.06	12.4	1.37	390	.0110	.12	54	.8	C	r
47	.034	5.50	13.5	1.31	159	.0105	.13	48	1.3	C	r
48	.034	5.89	14.4	1.34	242	.0125	.14	48			
Face		3.41							1.0	71C, 29W	p
Back		2.48								C	p
49	.035	5.64	13.4	1.28	73	.0160	.17	40	.9	C	woven (twill)
50	.036	6.47	15.0	1.27	199	.0100	.10	53	1.2	63C, 28R, 9W.	r
51	.036	6.50	15.0	1.48	216	.0090	.10	56	1.2	76C, 24W	r
52	.037	6.29	14.2	1.25	216	.0095	.10	61		59C, 41W	r
53	.037	6.35	14.3	1.20	269	.0130	.14	52			
Face		3.66							1.0	50C, 17Ss, 33W.	p
Back		2.69								C	p
54	.037	7.12	16.0	1.32	146	.0090	.09	58	1.4	36C, 33Ss, 31W	r
55	.038	6.27	13.8	1.25	214	.0135	.14	47			
Face		3.52							1.1	72C, 28W	p
Back		2.75								C	p
56	.038	7.28	16.0	1.35	125	.0115	.11	52	1.3	80C, 10R, 10W.	r
57	.038	7.48	16.4	1.39	177	.0115	.10	47	1.6	76C, 24W	r
58	.038	7.71	16.9	1.45	253	.0135	.14	49			
Face		4.72							.9	37C, 40R, 23W.	p
Back		2.99								C	p
59	.038	8.55	18.8	1.40	96	.0090	.09	53	1.4	40C, 25Ss, 35W.	r
60	.039	6.52	13.9	1.38	192	.0145	.14	46			
Face		3.88							1.1	34C, 32Ss, 34W.	p
Back		2.64								C	p
61	.039	7.00	15.0	1.30	190	.0115	.10	58	1.4	41S, 59W	r
62	.039	8.07	17.2	1.95	135	.0095	.09	52	1.3	72C, 28W	r
63	.040	7.20	15.0	1.14	163	.0105	.10	53	1.3	69C, 31W	r
64	.040	8.07	16.8	1.34	118	.0095	.09	52	1.7	36C, 33Ss, 31W.	r
65	.041	8.52	17.3	1.43	90	.0110	.09	48	1.4	71C, 29W	r

properties of underwear fabrics—Continued

13	14	15	16	17		18
Finish: b=bleached, d=dyed, dr=dyed random g=grey, m=mercerized	Wales or warp yarns per inch	Courses or filling yarns per inch	Yarn number (TYPP): C=cotton, CW=cotton and wool mixed, f=filling, R=rayon, S=silk, W=wool, w=warp	Twist—turns per inch: C=cotton, CW=cotton and wool mixed, f=filling, R=rayon, S=silk, w=warp, W=wool		Notes
				Single	Plied	
d	30	40	29.0	3	------	
b	30	29	24.5	17	------	
b	32	35	16.0	12CW, 23C	------	Single cotton-and-wool yarn and single cotton yarn knit as 1 in each course.
b	33	40	17.5	15	8	2-ply worsted yarns.
b	27	32	27.5	16	------	
g	27	31	25.5	19	------	
b	32	27	26.5	17	------	
						2-layer fabric.
bm	27	25	{26.0C, 18.5 CW	24 12	16 ------	1 course with 2-ply mercerized cotton yarn alternating with 2 courses single cotton-and-wool yarn.
b	26	25	25.5	26	24	2-ply yarns.
b	78	42	19.5w, 10.5f.	23w, 12f	------	Filling yarns were napped.
b	23	31	17.0	12CW, 21C, 2R.	------	2 courses with single cotton-and-wool yarn alternating with 2 courses containing a single cotton and a single rayon yarn knit as 1 in each course.
dr	24	38	18.0	15C, 9W	------	Alternate courses of single cotton and single worsted yarns.
dr	26	33	25.0	25C, 15CW	------	2 single yarns, 1 of cotton, and 1 of cotton-and-wool knit as 1 in each course.
						2-layer fabric.
b	27	26	{25.5S 16.0CW	17 11	13 ------	1 course of 2-ply spun silk yarn alternating with 3 courses single cotton-and-wool yarn.
b	27	26	24.5	26	24	2-ply yarns.
b	25	33	17.5	14CW, 12S	------	2 single yarns, 1 of cotton-and-wool, and 1 of spun silk, knit as 1 in cach course.
						2-layer fabric.
bm, dr	26	29	{26.5C 17.0CW	26 14	16 ------	1 course of 2-ply cotton yarn alternating with 2 courses of single cotton-and-wool yarn.
b	26	29	25.5	28	23	2-ply yarns.
b	27	29	{15.0C&R 18.0CW	15C, 2R 11	------ ------	5 courses of single cotton-and-wool yarns alternating with 1 course containing 2 single yarns, 1 of cotton and 1 of rayon knit as 1 yarn.
bm	26	32	{17.5CW 18.0C	14 19	------ 13	3 courses of single cotton-and-wool yarns alternating with 3 courses of 2-ply mercerized cotton yarns.
						2-layer fabric.
b	26	25	{17.5C&R 16.5CW &R	22C, 2R 14CW, 4R	------ 4	1 course of 2 single yarns, 1 of cotton and 1 of rayon, knit as 1, alternating with 3 courses of 2-ply yarns composed of a single cotton-and-wool and a single rayon yarn.
b	26	25	27.0	24	24	2-ply cotton yarns.
b	23	29	13.0	14CW, 10S	------	2 single yarns, 1 of cotton-and-wool and 1 of spun silk, knit as 1.
						2-layer fabric.
b	26	27	17.0	13CW, 11S	6	2-ply yarns, composed of 1 single cotton-and-wool and 1 single spun silk yarn.
b	26	27	25.0	28	22	2-ply cotton yarns.
b	26	37	21.5	16W, 10S	------	2 single yarns, 1 of worsted and 1 of spun silk, knit as 1.
b	25	34	17.5	14CW, 22C	------	2 single yarns, 1 of cotton-and-wool and 1 of cotton, knit as 1.
b	25	28	16.0	12CW, 18C	------	2 single yarns, 1 of cotton-and-wool and 1 of cotton, knit as 1.
b	28	35	17.0	12CW, 11S	------	2 single yarns, 1 of cotton-and-wool and 1 of spun silk, knit as 1.
b	27	34	16.5	16CW, 19C	------	2 single yarns, 1 of cotton-and-wool and 1 of cotton, knit as 1.

TABLE 1.—*Details of construction and*

1	2	3	4	5	6	7	8	9	10	11	12
Sample no.	Standard thickness	Weight	Density	Thermal transmission	Air permeability	Total compression	Compressibility	Compressional resilience	Coefficient of friction NN6N	Fiber: C=cotton, R=rayon, S=silk, s=spun, W=wool, w=weighted, numerals=contents %	Interlacing. f=fleeced, m=mesh knit, p=plain knit, r=rib knit, R=Rubenstein knit, w=warp knit
	In.	*Oz/yd*^{2}	*Lb/ft*^{3}			*In.*	*In*^{2}*/lb*	*Percent*			
66	.043	6.94	13.4			.0130	.11	50	1.2	36C, 32Ss, 32W.	r
67	.043	7.78	15.1	1.42	96	.0120	.11	44	1.3	C	r
68	.043	9.12	17.7	1.60	76	.0105	.09	50	1.3	78C, 22W	r
69	.044	6.95	13.2	1.35	209	.0135	.12	60	1.4	36Ss, 64W	r
70	.044	8.15	15.4	1.37	168	.0120	.10	56	1.3	37Ss, 63W	r
71	.044	8.44	16.0	1.66	120	.0095	.09	54	.8	67C, 33W	r
72	.045	7.20	13.3	1.43	216	.0150	.13	53	.9	C	r
73	.045	8.10	15.0	1.32	162	.0160	.14	48			
Face		3.97							1.1	61C, 39W	p
Back		4.13								C	p
74	.046	7.21	13.1	1.31	139	.0180	.14	44			
Face		3.67							1.1	81C, 19W	p
Back		3.54								C	p
75	.046	7.39	13.4	1.23	153	.0170	.12	58	1.2	37C, 63W	r
76	.046	8.79	15.9	1.31	102	.0120	.09	46	1.4	70C, 30W	r
77	.047	7.85	13.8	1.11	153	.0180	.14	48			
Face		3.99							1.2	30C, 70W	p
Back		3.86								C	p
78	.047	8.34	14.8	1.29	210	.0175	.14	44			
Face		4.20							1.2	83C, 17W	p
Back		4.14								C	p
79	.048	7.80	13.5	1.03	144	.0195	.15	43			
Face		3.81							1.1	61C, 39W	p
Back		3.99								C	p
80	.048	8.27	14.4	1.29	194	.0150	.11	58	1.3	W	r
81	.050	8.44	14.1	1.13	130	.0165	.13	42			
Face		4.32							1.0	52C, 48W	p
Back		4.12								C	p
82	.053	10.08	15.8	1.28	96	.0175	.12	48		C	r
83	.056	11.90	17.7		78	.0130	.10	52		99C, 1W	r
84	.058	10.28	14.8	1.14	143	.0150	.11	57		92C, 8W	r
85	.061	11.85	16.2	1.34	55	.0160	.10	40	1.3	C	r
86	.062	11.60	15.6	1.34	96	.0175	.10	57	1.0	36C, 64W	r
87a	.063	8.00	10.6	.92	249	.0205	.14	56		W	r
87b	.048	6.66	11.6			.0175	.13	59		W	r
88a	.064	8.20	10.7	1.03	157	.0230	.14	55	1.4	W	r
88b	.049	7.16	12.2			.0170	.13	61		W	r
89	.064	11.32	14.7	1.20	96	.0225	.13	48	1.1	95C, 5W	r
90	.066	12.02	15.2	1.03	159	.0195	.12	62	1.4	40C, 60W	r

properties of underwear fabrics—Continued

13	14	15	16	17		18
Finish: b=bleached, d=dyed, dr=dyed random, g=grey, m=mercerized	Wales or warp yarns per inch	Courses or filling yarns per inch	Yarn number (TYPP): C=cotton, CW=cotton and wool mixed f=filling, R=rayon, S=silk, W=wool, w=warp	Twist—turns per inch: C=cotton, CW=cotton and wool mixed, f=filling, R=rayon, S=silk, w=warp, W=wool		Notes
				Single	Plied	
b	23	33	16.5	15CW, 11S	------	2 single yarns, 1 of cotton-and-wool and 1 of spun silk, knit as 1.
b	20	26	12.0	9	------	
b	22	29	13.5	13CW, 17C	------	2 single yarns, 1 of cotton-and-wool and 1 of cotton, knit as 1.
b	21	30	17.0	9S, 12W	------	2 single yarns, 1 of spun silk and 1 of worsted knit as 1.
b	23	37	16.0	9S, 13W	------	2 single yarns, 1 of spun silk and 1 of worsted, knit as 1.
b	23	31	13.5	15C, 12CW	------	2 single yarns, 1 of cotton and 1 of cotton-and wool, knit as 1.
g	17	25	12.0	9	------	
					------	2-layer fabric.
b	25	26	16.5	12	------	Single cotton-and-wool yarns.
b	25	26	17.0	15	------	
					------	2-layer fabric.
b	26	27	16.5	12	------	Single cotton-and-wool yarns.
b	25	27	17.5	15	------	
b	26	32	19.0	23C, 14W	------	2 single yarns, 1 of cotton and 1 of wool, knit as 1.
dr	26	36	16.0	16CW, 22C	------	2 single yarns, 1 of cotton-and-wool and 1 of cotton, knit as 1.
						2 layer fabric.
{m	26	28	17.0C	20	13	1 course of 2-ply mercerized cotton yarn alternating with 3 courses of single cotton-and-wool yarn.
b	------	------	17.0CW	13	------	
b	26	27	17.0	16	------	
						2-layer fabric.
dr	24	28	17.0	14	------	
b	24	28	18.0	14	------	
						2-layer fabric.
dr	26	26	17.5	14	------	
b	26	27	18.0	15	------	
b	23	36	16.0	14	------	Each course consists of 2 single worsted yarns knit as 1.
					------	2-layer fabric.
dr	26	26	15.5	10	------	
b	26	26	14.5	11	------	
b	20	26	10.0	8	------	Back of fabric is brushed.
dr	18	21	{7.5C 7.5 C & CW	8 9C, 16CW	------ ------	7 courses of single cotton yarns, alternating with 1 course composed of a single cotton and a single cotton-and-wool yarn knit as 1. Back of fabric is slightly brushed.
dr	15	18	{8.5C 13.5 C & CW	8 18C, 16CW	------ ------	1 course of single cotton yarn, alternating with 1 course composed of a single cotton and a single cotton-and-wool yarn knit as 1. Back of fabric is slightly brushed.
b	18	32	9.5	8	------	
b	18	28	8.0	15C, 11W	------	2 single yarns, 1 of cotton and 1 of worsted, knit as 1.
dr	15	29	17.5	14	------	Each course consists of 2 single worsted yarns knit as 1. "a" is relatively loosely knit compared to "b."
dr	21	32	17.5	14	------	
b	16	25	17.0	18	------	Each course consists of 2 single worsted yarns knit as 1. "a" is relatively loosely knit compared to "b."
b	24	31	17.0	18	------	
dr	18	25	7.5	6	------	Back of fabric is slightly brushed.
dr	17	21	7.0	12C, 9W	------	Each course consists of 2 single yarns, 1 of cotton and 1 of worsted, knit as 1.

TABLE 1.—*Details of construction and*

1	2	3	4	5	6	7	8	9	10	11	12
Sample no.	Standard thickness	Weight	Density	Thermal transmission	Air permeability	Total compression	Compressibility	Compressional resilience	Coefficient of friction	Fiber: C=cotton, R=rayon, S=silk, s=spun, W=wool, w=weighted, numerals=contents %	Interlacing: f=fleeced, m=mesh knit, p=plain knit, r=rib knit, R=Rubenstein knit, w=warp, knit
	In.	*Oz/yd²*	*Lb/ft³*			*In.*	*In²/lb*	*Percent*			
91	.067	8.36	10.4	1.01	117	.0395	.21	45	1.5	C	pf
92	.067	11.34	14.1	1.17	67	.0270	.15	47	1.6	78C, 22W	r
93	.077	10.19	11.0	1.06	120	.0275	.14	62	1.2	W	r
94	.083	9.72	9.8	.86	88	.0430	.21	42	1.6	C	pf
95	.088	11.70	11.1	.86	67	.0452	.19	42	1.5	C	pf
96	.092	10.98	9.9	.66	74	.0530	.23	42	1.4	C	pf
97	.095	11.00	9.6	.72	57	.0525	.23	38	1.4	C	pf

properties of underwear fabrics—Continued

13	14	15	16	17		18
Finish: b=bleached, d=dyed, dr=dyed random, g=grey, m=mercerized	Wales or warp yarns per inch	Courses or filling yarns per inch	Yarn number (TYPP): C=cotton, CW=cotton and wool mixed f=filling, R=rayon, S=silk, W=wool, w=warp	Twist—turns per inch: C=cotton, CW=cotton and wool mixed, f=filling, R=rayon, S=silk, w=warp, W=wool		Notes
				Single	Plied	
dr-------	21	22	12.0	20g, 19dr	------	Each course consists of 2 single yarns and a backing yarn, knit as 1. Size of backing yarn unknown.
b--------	14	19	5.5	6	------	
b--------	16	30	8.0	7	------	
dr-------	19	26	12.5	21g, 21dr	------	Each course consists of 2 single yarns, and a backing yarn, knit as 1. Size of backing yarn unknown.
dr-------	23	29	12.5	18g, 23dr	------	Each course consists of 2 single yarns and a backing yarn, knit as 1. Size of backing yarn unknown.
dr-------	21	25	12.5	17g, 19dr	------	Each course consists of 2 single yarns and a backing yarn knit as 1. Size of backing yarn unknown.
dr-------	23	28	13.0	18g, 20dr	------	Each course consists of 2 single yarns and a backing yarn knit as 1. Size of backing yarn unknown.

The two-layer fabrics consisted of a "back" fabric composed entirely of cotton, and a "face" fabric composed of a single kind of fiber or a combination of fibers. (The term "back" is used in this paper to refer to the surface of the cloth that would normally be worn next to the body, while "face" designates the surface of the cloth that would normally be the outside surface when worn). The two layers are knit simultaneously and are joined together at regular intervals by having the yarn of the back fabric knit into the face fabric.

The yarns in the fabrics varied in size or "number" from 5 to 45,000 yd/lb,[3] and differed also with respect to the number of plies and the number of turns of twist per inch.

Some of the fabrics were in the grey state (i.e., not processed beyond knitting or weaving), others were bleached, dyed, or mercerized. Some were brushed or fleeced.

Two of the woven fabrics, numbers 11 and 19, were typical of the light weight cotton cloths used for men's union suits and are similar in weight and thickness to some of the knit fabrics. The weave is shown in figure 1(J). It is a small checked design in which 3 yarns are woven as 1 for every fourth yarn in both the warp and the filling. The third woven fabric, number 49, is a medium weight 3/1 twill weave cloth with a light nap on one side. It is similar in thickness and weight to some of the knit fabrics and is therefore of interest for comparison.

III. METHODS OF TEST

All fabrics were conditioned for test by exposure to an atmosphere of 65±1 percent relative humidity and 70° to 80° F temperature. The tests were conducted under these conditions.

(a) THERMAL TRANSMISSION

The apparatus [4] developed by Schiefer, shown in figure 2(A), was used for measuring the transmission of heat through the fabrics. The

[3] The TYPP system for designating the size or "number" of the yarn is used in this paper because of its convenience for comparing the sizes of the yarns of different fiber composition. The yarn number is the number of thousands of yards per pound of the yarn. This system was recently sponsored by E. D. Fowle in Textile World, 81,1470(Apr. 23, 1932).

[4] This apparatus was described briefly in the Bureau of Standards Technical News Bulletin no. 166, p. 15, (February 1931). An iron disk, painted with black lacquer, fits into the opening of a vacuum (thermos) jar. The disk is heated by means of a helical coil placed below it in the jar. A cavity in the disk is connected with a capillary and is filled with mercury which expands and contracts as the disk is heated or allowed to cool. The fluctuating mercury column in the capillary makes or breaks an electrical contact in a circuit which, operating through a relay, throws the current off or on in the heating coil and thus maintains the disk at a temperature which is maintained constant during the test to within ±0.1° F.

The specimen to be tested is clamped over the disk with the upper surface exposed to the standard atmosphere. The temperature of the standard atmosphere during a test is maintained constant to within ±0.2° F. The temperature of the upper surface of the disk is measured with a thermocouple. When a steady state of thermal equilibrium is established within the vacuum jar, that is, when there is no progressive change in the temperature of the disk, the test is begun. The intervals during which the current in the heating coil is off and on are timed with stop watches. Usually 10 current-off and 10 current-on intervals are taken for a test. The total time of a test usually varies between 20 and 30 minutes. The current indicated by an ammeter and the room temperature are recorded at frequent intervals during a test. The quantity of heat supplied to the vacuum jar per unit time per degree difference in temperature during a test is computed from the expression $\frac{K I^2 \epsilon t_c}{[\epsilon t_c + \epsilon t_o] T}$ where I denotes the current; t_c, a current-on interval; t_o, a current-off interval; T, the average temperature difference between the upper surface of the disk and the room; and K, a constant which includes the resistance of the heating coil and factors for expressing the result in convenient units. Part of the heat input is dissipated through the specimen and the remaining part is lost through the apparatus. This end loss through the apparatus was determined for a thick layer of cork of known thermal conductivity in conjunction with a number of fabrics. It was found to increase linearly with the gross heat input, the increase being about 10 percent for a 100 percent increase in the gross input. A correction for end loss, depending upon the gross heat input, was applied to the gross heat input for each fabric. This value divided by the area of the disk is the quantity of heat transmitted per unit time per unit area of fabric per degree difference in temperature.

value reported is the quantity of heat passing through 1 ft ^{2} of fabric in 1 hour for each degree difference in temperature between a horizontal black hot plate and the air above the fabric when one side of the fabric is in contact with the hot plate and the other side is in contact with still air. The temperature of the hot plate for the values reported was maintained at 102 $\pm 2°$ F, approximately body temperature.

(b) AIR PERMEABILITY

The air permeability of the fabrics was measured with the apparatus developed by Schiefer and Best,[5] shown in figure 2(B). The fabric is clamped between two orifice rings under a slight tension and air is drawn through it and through a calibrated orifice by means of a suction fan. The drop in pressure across the fabric and that across the orifice is observed. From this is calculated the rate of air flow through the fabric at a given pressure drop across it. Each value in the table is the number of cubic feet of air passing through 1 ft ^{2} of the fabric in 1 minute when the air pressure on the one side of the fabric is equivalent to that of 0.3 in. of water above that on the other side.

(c) THICKNESS AND COMPRESSIONAL CHARACTERISTICS

The "standard thickness", "total compression", "compressibility", and "compressional resilience" of the fabrics were measured with the compressometer shown in figure 2(C), according to the method devised by Schiefer.[6] These properties appear to be useful criteria of the "handle" or "feel" of fabrics when they are squeezed between the fingers and are related to what are commonly designated as softness and springiness of underwear fabrics, which may be important attributes.

In this test, the specimen is placed between the plane parallel surfaces of the anvil and the presser foot, which is a circular disk, 1 inch in diameter. Pressure is applied gradually through the foot by turning the knob at the side of the instrument. The pressure on the specimen is indicated by the upper dial, and the corresponding distance between the presser foot and the anvil, that is, the thickness of the specimen at this pressure, is indicated by the lower dial. When the pressure reaches 2 lb/in.^{2} the knob is turned in the opposite direction and the pressure on the specimen is thus gradually released. The thickness is observed at a series of increasing and decreasing pressures.

The thickness of a knit underwear fabric is purely a matter of definition. The "standard thickness" reported here is the distance between the plane parallel surfaces of the anvil and the presser foot of the thickness gage when the pressure on the specimen has been gradually increased to 1 lb/in^2 The total "compression" is by definition the change in thickness when the pressure is increased from 0.1 to 2.0 lb/in.^{2} The "compressibility" is the ratio of the decrement in thickness to the increment in pressure for unit thickness at a pressure of 1 lb/in.^{2} The "compressional resilience" is the amount of work recovered from the specimen when the pressure is decreased

[5] Herbert F. Schiefer and Alfred S. Best, *A portable instrument, for measuring air permeability of fabrics.* B.S.J. Research **6**, 51(1931);RP261.

[6] Herbert F. Schiefer, *The compressometer, an instrument for evaluating the thickness, compressibility, and compressional resilience of textiles and similar materials.* B.S. J.Research **10**,705(1933);RP561.

from 2.0 to 0.1 lb/in^2 expressed as a percentage of the work done on the specimen when the pressure is increased from 0.1 to 2.0 lb/in.^{2}

(d) COEFFICIENT OF FRICTION

The coefficient of friction between two pieces of the same material was tested with Mercier's equipment [7] (fig. 2D) which employs the principle of the inclined plane. The faces of two pieces of the same fabric were opposed on the inclined plane and sliding block with the ribs or wales running parallel to the direction of motion. These conditions were selected because they represent the usual direction in which outer clothing is pulled over underclothing.

It is recognized of course that the value obtained depends upon whether the face or back of the fabric is tested and the orientation with reference to the direction of the wales and courses; also that a different series of values would be obtained if the fabrics were tested against a second or "standard" fabric. Since the coefficient of friction depends on the nature of the materials and the smoothness of the surfaces, it is to be presumed that in such a series, the various fabrics would be found in the same sequence.

IV. DISCUSSION OF RESULTS

It is obvious that no one set of test conditions will simulate all conditions of use of underwear fabrics. Most of the fabrics studied are easily stretched and will change materially in thickness, weight per unit area, and in surface characteristics with movements of the wearer of garments made from them. The conditions of test used in this work are more or less standard in textile testing laboratories. The interpretation of the results in terms of the use of the fabrics is definitely limited by the test conditions and much work is needed before a clear picture can be drawn. However, in general, two fabrics which differ significantly in a property in the test used are expected to differ in a similar way though perhaps to a different degree under some other set of conditions. Exceptions to this statement are to be expected, but a consideration of the nature of the particular fabric and the changes in the test conditions will usually explain if not anticipate the exceptional results. It is believed that the range in properties of the group of fabrics will not be materially changed by measurements conducted under other conditions or by modifications of the fabrics brought about by laundering.

The results of this study are summarized in table 1. Since the thinnest and lightest-weight fabrics are usually made of continuous filament silk or rayon yarns, it is not surprising to find them grouped together in the fore part of the table. These are followed by the fabrics composed of spun silk or spun rayon fibers, then by those made from cotton, wool, or mixtures of fibers, and finally by the fleece-lined fabrics.

The results given in the table show that, in general, increasing thickness is accompaied by increasing weight, decreasing air permeability, and decreasing thermal transmission, as was to be expected from experience and from the findings of other investigators. However, very precise correlation between these different factors is not to be expected in a series of fabrics such as this one in which the different

[7] Alfred A. Mercier, *Coefficient of friction of fabrics.* B.S. J. Research 5, 243(1930);RP196.

materials are simply representative of those on the market. Most valuable studies could be made by constructing series of fabrics in which only one element is varied.

The properties of fabrics numbers 20, 23, 24, 27, and 28 are particularly interesting for these fabrics were knit on the same machine from yarns of approximately the same size, but of different fiber compositions. The values for the thermal transmission are practically the same except for fabric number 23, of spun silk which has a comparatively low value. This fabric is made from yarn of relatively low twist which may account in part at least for this difference and also for the fact that it has the lowest air permeability of the five fabrics. It will be noted that fabric number 23 has a slightly greater number of wales per inch than the other fabrics in this series. The differences in air permeability may be in part attributable to the differences in the ability of the fabrics to stretch which is evident on handling them. A small tension is applied to the fabrics during this test, and doubtless some of them stretched more than others. The wool fabric, number 28, is the thickest and lighest of the series, has an appreciably greater total compression, and is more compressible than any of the other fabrics, due no doubt to the resilience of the wool fiber.

Fabrics numbers 30 and 35 were similar, except that the former was bleached and the latter was in the grey state. For these particular fabrics, bleaching increased the thermal transmission and decreased the permeability to air, total compression, compressibility, and compressional resilience.

In order to show more clearly the interrelations of the properties of the knit fabrics, a number of charts are presented. Different symbols are used in the charts to designate the type of interlacing of the yarns and the fiber compositions so that the effects of these characteristics may be noted.

The thickness and weight of each fabric is plotted in figure 5. In a general way, these properties are proportional to each other for all the fabrics except the fleece lined and three of the wool rib knit fabrics which are relatively thick for their weight.

The air permeability is plotted against the thermal transmission in figure 6. This chart indicates that for any specific air permeability, considerable variation in thermal transmission is possible and vice versa.

The thermal transmission and air permeability of each fabric is plotted against its thickness and its weight in figure 7. In general, both thermal transmission and air permeability are relatively high for the thin or light fabrics and relatively low for the thick or heavy fabrics. It is clear, however, that fabrics having a given thickness or weight can be made in a considerable range of either thermal transmission or air permeability. The tendency for several of the types of fabrics tested to be grouped together in these figures will be noted. It will also be observed that the warp knit fabrics tested are in general less permeable to air than plain knit fabrics of comparable thickness but slightly greater weight. The values for the thermal transmission of these fabrics cover a relatively wide range which is comparable for the two types. With one exception, the fleece-lined fabrics are the thickest fabrics tested and have lower values for thermal transmission than other fabrics of comparable weights. They are grouped with rib-knit fabrics of similar weights with respect to air permeability.

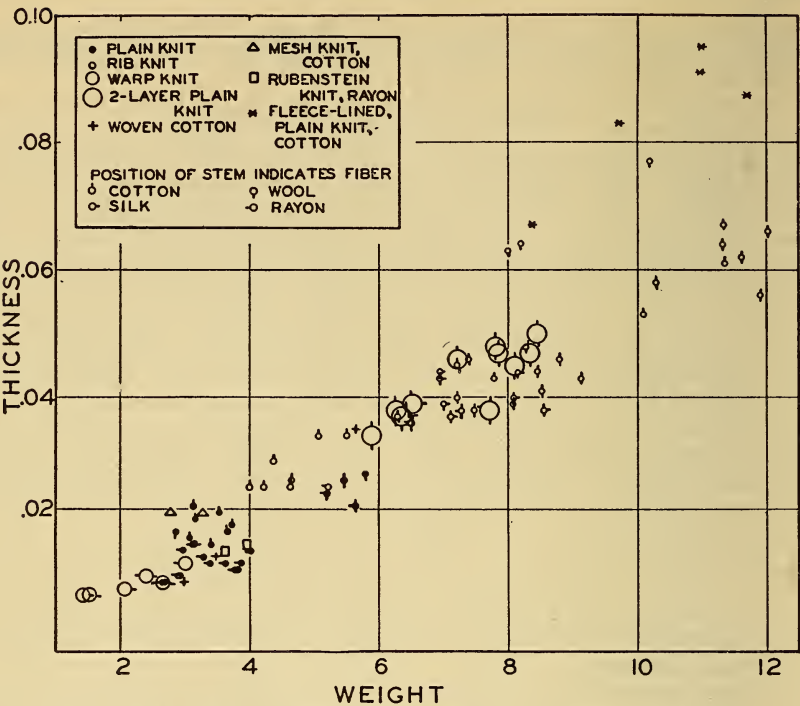

FIGURE 5.—*Relation between thickness (in.) and weight (oz/yd²).*

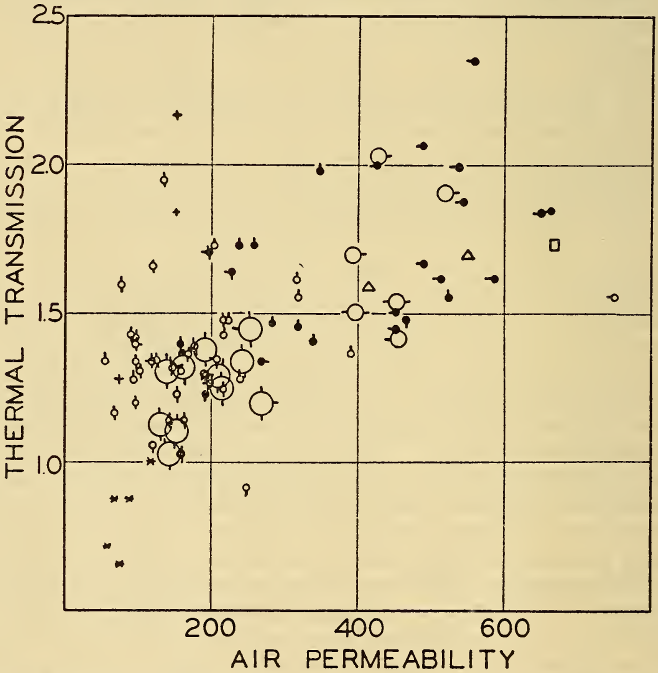

FIGURE 6.—*Relation between thermal transmission (Btu/hr ft² F) and air permeability (ft³/min ft², at pressure drop of 0.3 in. water).*

Figures 8, 9, and 3, (p. 313), show some relationships of the compressional characteristics of the fabrics. Total compression correlates well with thickness, figure 6, for the whole group of fabrics, and even better when the fabrics of similar construction are compared; for example, the

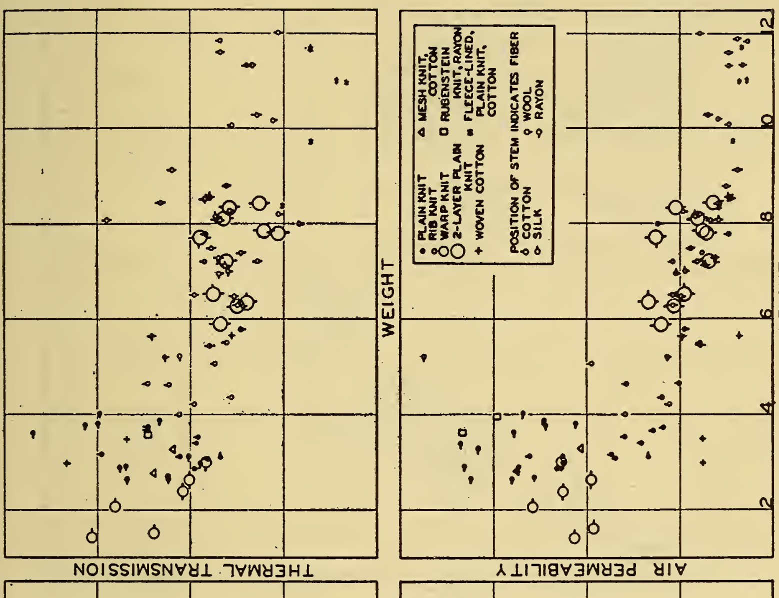

FIGURE 7.—*Thermal transmission (Btu/hr ft² F) and air permeability (ft³/min ft², at pressure drop of 0.3 in. water) in relation to thickness (in.) and weight (oz/yd²).*

group of fleece-lined fabrics, the two-layer fabrics, the rib-knit fabrics. The compressibility decreases with increasing density (i.e., the weight in pounds of 1 cubic foot of fabric based on the standard thickness) figure 9, though for any value of either property, there are fabrics having a range of values with respect to the other property. The compressional resilience of the majority of the fabrics lies between 45 and 60 percent, figure 3.

The distribution of the fabrics with respect to coefficient of friction between two pieces of the same fabric when the faces are opposed is shown in figure 4, (p. 313). As was to be expected, the fabrics made from the continuous filament silk or rayon yarns have the lowest coefficient

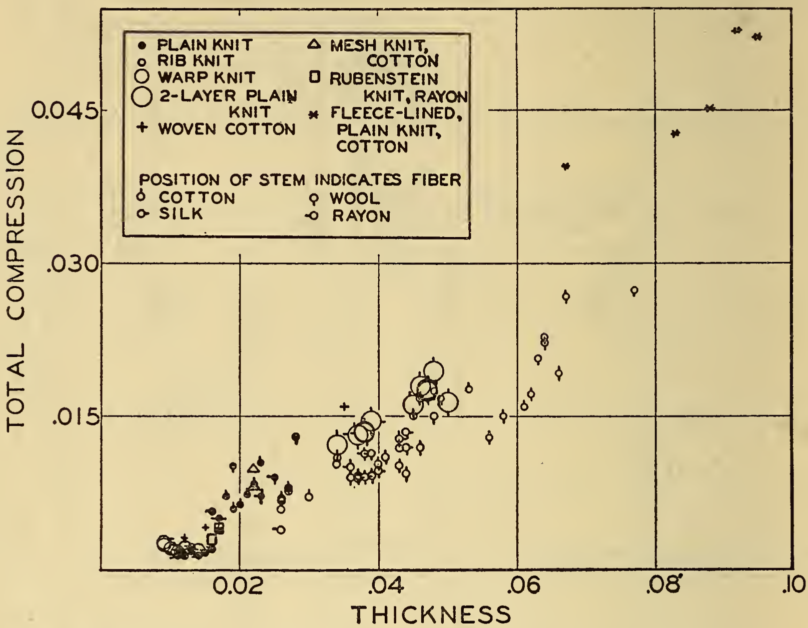

FIGURE 8.—*Relation between total compression (in.) and thickness (in.).*

of friction. This property may be taken as a measure of the smoothness of a fabric, which is no doubt indicative of the ease with which that fabric would slip over another one, as for example in the case of outerclothing pulled over underclothing.

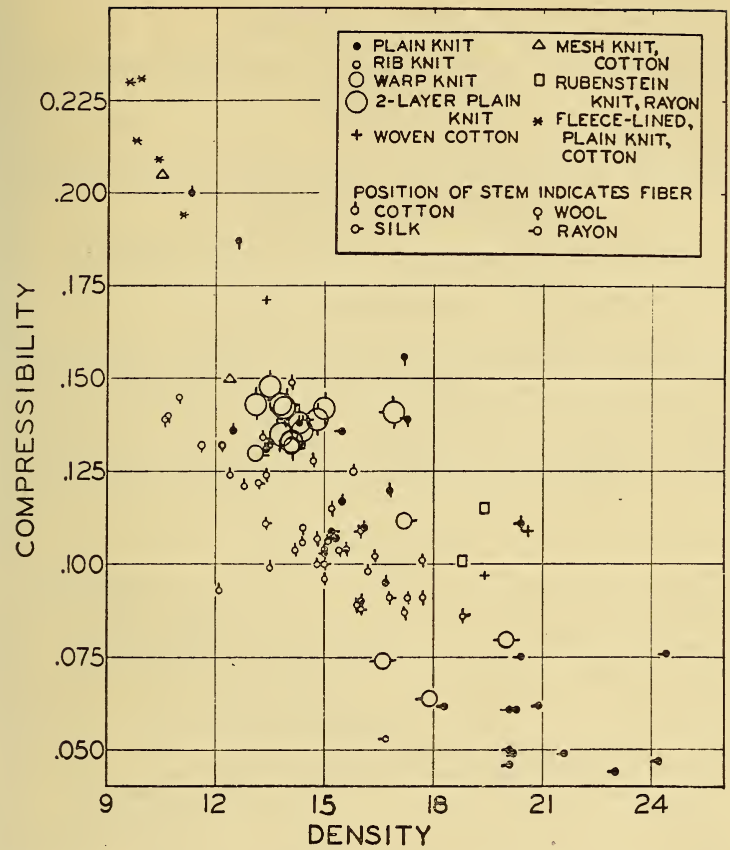

FIGURE 9.—*Relation between compressibility* (in^2/lb) *and density* (lb/ft^3).

WASHINGTON, July 13, 1934.