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AN INVESTIGATION OF A THERMAL ICE-PREVENTION SYSTEM FOR A CARGO AIRPLANE. IX – THE TEMPERATURE OF THE WING LEADING-EDGE STRUCTURE AS ESTABLISHED IN FLIGHT

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SUMMARY

As part of an investigation of a thermal ice-prevention system for a cargo airplane the NACA has completed flight measurements of the structure temperatures prevailing in the wing outer panel of the airplane. Sections of the wing panel were altered to represent three commonly employed types of thermal ice-prevention systems.

Temperatures of the structural components of the forward portion of the wing were obtained for various normal operating conditions of the airplane at 5000, 10,000, and 15,000 feet pressure altitude. Controlled tests were made to determine the effects of heated-air temperature, heated-air flow rate, airspeed, and altitude on the structure temperatures.

The structure temperature data have been compiled in a table which should provide an indication of the structure temperatures that prevail in a typical air-heated wing.

The data obtained indicate that the structure temperatures which prevail in a thermal ice-prevention system are sufficiently high to merit some consideration in the design of stressed members. The variables controlling the structure temperatures were analyzed, and the heated-air temperature was established as the dominant variable. The structure temperatures increased in almost direct proportion to increases in heated-air temperature, but were much less affected by changes in air flow rate, airspeed, and altitude over the test range.

The conclusion is reached that the most direct method for increasing deficient surface temperatures is to increase the temperature of the heated air with the understanding, however, that

this method will result in a larger rise in structure temperature than would occur if the surface temperature were raised by increasing the heated-air flow rate.

INTRODUCTION

As part of an investigation of a thermal ice-prevention system for a typical transport or cargo airplane, the NACA has undertaken an examination of the possible deleterious effects resulting from the circulation of heated air adjacent to the airplane structure. This problem was not treated during the initial stages of the development of thermal ice-prevention equipment for airplanes by the NACA (references 1 to 8) as it was considered to be of secondary importance.

The possible deleterious effects resulting from air heating of the aluminum alloy structure of an airplane are (1) thermal stresses generated by the existence of temperature gradients in the structure, (2) increased susceptibility of the structure to corrosion, (3) reduction of the yield and ultimate strength of the structure while it is at elevated temperatures, (4) creep of the structure at elevated temperatures even when the stress is below the yield point, and (5) artificial aging of the structure. The subject of thermal stresses was treated in the seventh report of this series, reference 9. A metallurgical examination of the structure of the cargo airplane employed in the present tests (reference 10) indicated that no corrosive effects were noted which could be attributed to the basic principle of using free stream air as the heat-transfer medium in the internal circulatory system of the airplane. The reduction in ultimate and yield strength, and also artificial aging, are dependent on the maximum temperatures achieved by the structure and length of time that the structure is maintained at these temperatures. Creep of the structural material is dependent on these factors and also the stress imposed on the structure.

The effects of temperature on the physical characteristics of several aluminum alloys have been quite extensively investigated (references 11 to 14). The remaining problem for the aircraft designer, therefore, is to predict the structure temperatures that will occur during operation of the thermal ice-prevention system.

The establishment of basic heat-transfer data which would be applicable to the computation of the temperature gradients in all airplane wings was not considered to be practicable. It was believed, however, that structural temperature data for a typical thermal ice-prevention system would at least provide some indication of the degree of temperature rise to be anticipated, and might provide a basis for estimating maximum temperatures in future similar installations. Accordingly, the present investigation was undertaken to determine the structure temperatures in the left wing outer panel of the cargo airplane of references 3 to 9. The investigation included tests at various normal operating conditions, and other tests in which the variables of heated-air flow rate, heated-air temperature, airspeed, and altitude were individually varied to determine the effect of each variable on the structure temperatures.

Description of Equipment

The cargo airplane altered by the NACA to provide for thermal ice-prevention is shown in figure 1. The thermal ice-prevention equipment installed in the airplane is described in detail in reference 5. The wing outer panel, which is the concern of the present investigation, is of a distributed flange-type construction with spars at 30 percent and 70 percent chord. The airfoil sections of the outer panel vary from an NACA 23017 section (198 in. chord) at the root (station 0) to an NACA 4410.5 section (66 in. chord) at the tip (station 412). All of the wing structural material is 24ST Alclad aluminum alloy. A typical section of the leading edge showing the alterations made to provide the thermal ice-prevention system is shown in figure 2. Typical details of the wing structure are illustrated in figures 3, 4, 5, and 6. Heated air was supplied to the outer panel from an exhaust gas-to-air heat exchanger (reference 5). A valve was included in the ducting from the heat exchanger to the wing to control the heated-air flow rate. The flow of heated air within a section of the wing is illustrated in figure 2. The flow of heated air throughout the wing outer panel was similar to that shown in figure 2 except that no nose rib liner was employed between stations 82 and 142 and no nose rib liner nor nose ribs were employed between stations 292 and 412. This arrangement (fig. 7) provided data for three different types of internal structure, all representative of possible thermal-system designs.

The temperature data were obtained from the thermocouples installed throughout the wing leading-edge structure. In the case of the internal structure, iron-constantan thermocouples were flash-welded to the structure. For wing-surface temperatures, surface-type thermocouples (iron-constantan thermocouples rolled to 0.002 in. thickness) were cemented to the skin. The locations of the various thermocouples are shown in figure 8. Thermocouples for which no data were obtained have been omitted in figure 8 and, therefore, some numbers are missing in the thermocouple numerical order.

In order to measure the temperature and flow rate of the heated air delivered to the wing outer panel, use was made of the venturi meter and temperature survey in the duct from the heat exchanger to the wing outer panel which are described in reference 5.

The thermocouple temperatures were recorded by a self-balancing potentiometer. The airplane flight conditions were obtained from the standard aircraft instruments, and the rate of climb was determined by observing the change in pressure altitude for one-half minute intervals.

TESTS

Temperature data for the wing outer-panel structure were obtained for various operating conditions of the airplane. Data were obtained during ground warm-up, take-off, and during flight in clear air at approximately 5,000, 10,000 and 15,000 feet pressure altitude with the airplane flown at various normal operating conditions. One set of data was obtained in clouds and a similar set was obtained in clear air (no visible moisture) to illustrate the effects of atmospheric moisture on the structure temperatures. Tests were also made during flight in clear air to investigate the effects of variations of heated-air flow rate, heated-air temperature, airspeed, and altitude on the structure temperatures. The heated-air flow rate was varied by controlling the valve in the duct between the heat exchanger and the wing outer panel. The heated-air temperature was varied by control of the power output of the left engine and adjusting the power output of the right engine to provide the airspeed desired.

RESULTS AND DISCUSSION

The recorded structure temperature data for the three types of construction are presented in table I. The values of airspeed given are corrected indicated airspeeds. The ambient-air-temperature values in the table have not been corrected for the effects of kinetic heating. The structure temperature data are presented as temperature rises above ambient-air temperature in the table in order to provide a common basis for comparison of the data. The actual structural temperatures that would prevail at any given ambient-air temperature may be approximated by the addition of the ambient-air temperature to the temperature rises given in table I.

The structure temperatures measured for the three variations of construction used in the left-wing outer panel (fig. 7) are not directly comparable because the airfoil section changes throughout the span both in shape and size and the heated air flow diminishes in quantity and temperature as the flow progresses spanwise. However, the presentation of the data for the three designs will give some indication of the temperature to be expected in three commonly employed types of thermal ice-prevention systems.

The maximum structure temperature rises measured were obtained during climb of the airplane at 15,000 feet pressure altitude (test 13 of table I). The highest values of temperature rise for the various components of the thermal ice-prevention system measured during this test were: nose rib lines, 393° F; baffle plate, 356° F; nose rib, 335° F; inner skin, 317° F; and outer skin, 235° F.

By assuming that operation of the thermal system could be limited to a maximum free air temperature of 32° F, the actual temperatures of these structural components would be 425° F, 388° F, 367° F, 349° f, and 267° F, respectively. An indication of the effect of temperatures of this magnitude on the yield and ultimate strength of 24ST Alclad is obtainable from reference 11. In this reference, the strength reduction is shown to be a function of both maximum temperature and time. For a duration of 15 minutes at the temperatures previously listed, the reduction of yield and ultimate strength in percent of the values at 75° F for the wing components would be: nose rib liner, 16 percent (yield) and 29 percent (ultimate); baffle plate, 15 and 22 percent; nose rib, 14 and 18 percent; inner skin, 13 and 16 percent; and outer skin, 6 and 10 percent. For times longer than 15 minutes up to at least 10 hours, the yield strength remains constant or increases and the ultimate strength remains constant or decreases, depending on the temperature considered (reference 11).

It should be pointed out that the airplane tested had no provisions for automatically controlling the heat flow to the wing. Consequently, at low-speed high-power conditions such as those of test 13, the heat delivered to the wing was considerably in excess of that required for ice prevention. (An average skin-temperature rise of 100° F in dry air at the leading edge is considered satisfactory for ice prevention for the speed range of the test airplane, as given in reference 3.)

The heated-air temperatures which prevailed during test 13 (an average air-temperature rise of 424° F at station 37) were considerably in excess of those that provided satisfactory ice prevention during tests of the thermal system in natural icing conditions (reference 6). If the maximum heated-air temperature in the wing were regulated to that required for ice prevention under any normal flight conditions of the airplane, the structure temperatures would be considerably lower. Reference 6 indicates that the maximum actual temperature of the heated air leaving the heat exchangers for the wings was approximately 340° F during the tests in natural icing conditions. The maximum temperature in the wing duct would be below this value. If the heated-air temperature in the wing duct did not exceed a maximum of 320° F in a 32° F atmosphere, the maximum structure temperature rises that would prevail would be approximately: nose rib liner, 266° F; baffle plate, 240° F; nose rib, 225° F; inner skin, 212° F; and outer skin, 155° F. These values were approximated from the relationship of heated-air temperature to structure temperature as discussed in detail later in this report. They can be accepted as valid for any flight condition within the test range wherein the air temperature in the wing duct is 320° F in a 32° F atmosphere. If the structure were subjected to these temperature rises for 15 minutes in a 32° F atmosphere, the reduction in the yield strength in percent of the value at 75° F would be approximately 3 percent for the outer skin and 4 to 9 percent for the baffle plate, nose rib liner, nose rib, and inner skin. The corresponding ultimate strength reductions would be approximately 6 percent and 9 to 11 percent, respectively. These values are considerably lower than those obtained without any regulation of the thermal system. However, they are sufficiently high to illustrate that the structure temperatures which prevail in a thermal ice-prevention system merit some consideration in the design of stressed members.

The effects of creep and artificial aging of Alclad 24ST aluminum alloy are discussed in references 12 and 14, respectively. Creep is dependent on the structure temperature, the time interval that a member is subjected to the temperature, and the stress imposed on the member during the time interval. Artificial aging may produce a change in physical properties which will remain after the structure cools, and the extent of aging is dependent on the temperatures reached and the length of time that the member is subjected to these temperatures. The data of references 12 and 14 indicate that the effects of creep and artificial aging are negligible for Alclad 24ST aluminum alloy at temperatures below 300° F. At temperatures above this value the design of stressed members may require the consideration of these factors. Data presented in reference 10 show that artificial aging was present in the section of the wing of the C-46 airplane where the heated air impinged upon the baffle plate on entering the wing. The result was a decrease in elongation, a marked increase in yield strength and a slight increase in ultimate strength.

Attempts have been made to predict the structure temperatures prevailing in a heated wing and the attendant effects on the structure. Insufficient heat-transfer data are available, however, to analyze, with any accuracy, the heat flow in the complex structure of a wing. The data of this report, however, can serve to aid in the prediction of structure temperatures by showing the effect of the variables of heated-air temperature, air-flow rate, altitude, airspeed, and free water in the atmosphere on the structure temperatures measured.

The effects of heated-air temperature (tests 16 to 20) and of heated-air-flow rate (tests 17, 21, and 22) are presented in figures 9 and 10, respectively. The data plotted in these figures are representative of the structure temperature rises throughout the wing. An analysis of figure 9 indicates that the structure temperatures increase in almost direct proportion to the increase in heated-air temperatures. For example, if the heated-air temperature is increased 40 percent, all of the structure temperatures are increased by approximately 40 percent. Figure 10 indicates that a change in flow rate of 1000 pounds per hour changes all of the structure temperatures by about 11° F. Thus a change in air-flow rate affects the low structure temperatures more, in proportion, than it affects the high structure temperatures. For example, if the flow rate is increased 40 percent from 3000 pounds per hour, figure 10 indicates that S-2 (a skin temperature) would be increased by about 19 percent, while M30 (a baffle-plate temperature) would be increased by only approximately 6 percent.

In the case of heated-wing design, therefore, which was deficient in surface-temperature rise but critical in internal-structure temperature, the more desirable method of increasing the skin temperature would be to increase the air-flow rate. This would result in the achievement of the desired skin temperature at a minimum increase in structure temperature. If the structure temperatures were not critical, however, the skin temperatures could be increased most efficiently by increasing the heated-air temperature. In the case of the present tests the range of air-flow rates was not large and, consequently, the structure-temperature data were almost independent of air-flow rate.

An examination of tests 6 and 23 indicates that a change in airspeed from 114 to 162 miles per hour had little effect on the structure temperatures. Tests 9 and 19 show that a change in altitude from 14,900 feet to 10,000 feet had little effect on the structure temperatures. These four tests are the only ones which can be directly compared to show the effects of changes in airspeed and altitude. A further indication that the structure temperatures were practically independent of altitude, airspeed, and air-flow rate for the range of these tests, however, can be obtained by plotting structure-temperature rise as a function of heated-air temperature rise and noting the scatter of the data. This has been done in figure 11, in which all of the data for several thermocouples (except tests 1 and 15) are presented. The curves of figure 9 have been reproduced on figure 11 as a basis of comparison. Figure 11 shows that the test variations in flow rate (3075 lb per hr to 6000 lb per hr), pressure altitude (S.L. to 15,900 ft), and indicated airspeed (114 to 170 mph), had little effect on the structure temperatures, and that all of the structure-temperature data obtained may be considered as a function of only duct-air temperature without serious error.

The effect of the presence of free water in the air on the structure temperatures is evident from a comparison of tests 14 and 15. The principal influence of the water is to produce a reduction of leading-edge surface temperatures as shown for wing station 112 in figure 12. The region of surface-temperature reduction corresponds approximately to the area upon which the cloud drops impinge, and little effect is noted rearward from that area. Thus, the nose-rib temperatures aft of 5 percent chord and the baffle-plate temperatures are not influenced appreciably by flight in clouds. The effect of free water on structure temperatures are of interest; however, clear-air structure temperatures should be used for the design selection of maximum structure temperatures, since thermal systems are usually operated constantly in potential icing conditions and the critical structure temperatures would be encountered during periods of flight between clouds.

At several points the present data are not in agreement with conclusions presented in reference 15. This reference points out that the inner skin temperature may be approximately the same as the outer skin temperature, as a result of almost perfect conduction of heat from the inner to the outer skin. The reference suggests, therefore, that the effective surface for the removal of heat from the heated air in the double-skin region is the sum of the surface areas of the inner and outer skin. The data of this report show that, at least for the test airplane, the average temperature rise of the inner skin was 1.5 to 2.0 times the average temperature rise of the outer skin. This result would indicate poor heat transfer between the skins, and that the conservative design assumption would be to assume that only a small portion, if any, of the heat flow from the heated air to the inner skin is eventually transferred to the outer skin. Reference 15 also points out that the temperature of the baffle plate may be within a few degrees of the outer skin temperature. The data of this report (table I) show the baffle-plate temperature rises to be 2 to 3.5 times as high as the outer skin average temperature rise, which would prove of importance if the use of the baffle as a spar is contemplated.

CONCLUSIONS

The following conclusions are based on flight data obtained during the operation of a typical thermal ice-prevention system, and are applicable to thermal systems similar to the one tested:

1. The reduction of ultimate and yield strength resulting from the elevated temperatures of the structural components of a heated wing merits consideration in the design, particularly for a system in which the heated-air temperatures are not regulated.

2. The structure temperatures are primarily affected by the temperature of the heated air employed, and increase almost in direct proportion to the increase in heated-air temperature.

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TABLE I.– STRUCTURE TEMPERATURES MEASURED IN THE LEFT-WING OUTER PANEL OF THE TEST AIRPLANE

PART I.– AIRPLANE OPERATING CONDITIONS

Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Flight conditions	Ground warm up	Take-off	Maximum range	1900 rpm cruise	Maximum allowable speed	Maximum range	1900 rpm cruise	Maximum allowable speed	Maximum range	1900 rpm cruise	Maximum allowable speed	Climb	Climb	(a)	Clouds	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Airplane velocity IAS, mph	0	141	124	159	167	114	154	167	134	154	164	140	134	170	167	138	135	134	136	135	136	135	162
Pressure altitude, ft	Sea level	0 to 3,700	4,800	4,100	4,100	10,000	10,000	10,000	14,900	15,900	14,900	Av 14,000	Av 14,600	1,100	900	9,500	10,150	10,100	10,000	10,000	10,050	9,900	10,000
Ambient-air temperature, °F	80	78	72	73	75	51	54	55	34	30	35	Av 42	Av 43	69	58	59	57	47	44	49	58	58	50
Average air temperature from ex-exchanger, °F	263	467	356	383	393	389	409	400	396	411	414	443	486	319	302	201	303	341	392	421	305	305	390
Air-flow rate lb/hr	2,735	5,240	4,270	5,375	5,900	3,580	4,590	5,190	3,670	4,010	4,700	3,890	3,490	6,000	5,960	3,360	3,500	3,680	3,730	3,630	3,075	4,090	3,500
Heat flow rate, Btu/hr	110,000	493,000	293,000	401,000	452,000	292,500	372,000	431,000	321,000	369,000	429,000	376,000	372,000	360,000	350,000	125,000	208,000	261,500	313,000	325,500	184,000	243,800	287,500
Average rate of climb, fpm	–	–	–	–	–	–	–	–	–	–	–	210	300	–	–	–	–	–	–	–	–	–	–

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(a) Controlled tests to determine the effect of heated-air temperature, air flow rate, altitude and airspeed on the structure temperatures.

TABLE I. - CONTINUED

PART 2. - TEMPERATURE RISE ABOVE AMBIENT-AIR TEMPERATURE AT STATION 37, °F

Thermocouple No. \ Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S1	44	73	50	61	64	60	70	69	70	78	78	72	82	49	47	25	44	52	63	63	41	49	57
S2	47	86	58	79	80	69	96	91	95	113	107	98	121	70	51	33	62	68	84	83	59	70	82
S3	53	137	96	122	130	110	142	141	135	154	153	147	168	102	39	52	93	104	124	129	88	99	125
S4	40	124	98	109	108	114	124	118	123	133	131	131	147	89	57	50	81	100	115	114	76	90	101
S5	40	100	76	81	82	92	91	88	95	97	97	95	111	64	55	39	62	74	86	87	58	69	74
S6	13	38	27	34	35	31	38	38	36	41	42	35	52	27	21	14	24	29	34	33	23	29	30
M7	37	92	60	77	83	66	84	88	78	89	94	83	94	66	62	30	51	61	73	73	47	59	69
M8	57	131	85	107	114	98	118	121	111	128	131	121	135	91	86	40	71	86	105	108	57	79	100
M9	77	173	124	144	151	144	164	164	160	175	182	160	193	120	115	63	110	131	157	164	106	116	151
M10	89	199	144	163	173	167	187	189	185	200	209	183	222	137	132	76	129	155	182	191	125	136	177
M11	96	233	161	188	198	186	212	211	204	225	230	226	254	158	153	79	142	166	200	210	135	148	194
M12	110	269	187	217	229	216	244	243	237	259	264	262	293	182	178	95	164	194	232	245	158	171	226
M13	152	348	255	279	288	301	320	312	323	339	343	358	393	230	227	129	222	266	315	332	221	224	305
M14	87	217	148	178	188	170	201	200	190	215	220	211	250	152	141	75	130	154	186	195	126	139	182
M15	73	180	122	153	163	139	171	172	161	185	187	180	196	128	115	59	105	124	149	155	100	115	149
M16	101	255	175	207	218	202	233	232	225	250	254	249	279	175	168	89	154	183	219	231	149	163	214
M17	83	226	154	190	200	176	211	212	200	225	229	223	249	162	141	80	136	161	194	202	131	147	189
M18	83	220	151	180	189	176	205	202	195	218	221	216	242	153	120	80	134	161	191	197	130	144	184
M19	102	265	184	215	226	213	241	240	234	256	262	260	289	182	164	95	161	192	229	240	155	169	222
M22	70	206	151	171	176	173	191	190	188	201	203	205	227	142	124	73	123	149	180	185	120	133	166
M25	99	263	188	213	224	219	238	238	235	252	257	255	287	182	174	91	158	190	225	238	153	169	216
M26	149	333	240	267	277	283	302	301	304	320	326	334	374	226	221	125	210	248	292	312	207	216	288
M27	87	235	169	190	198	198	212	211	211	225	227	229	255	160	151	81	139	168	200	210	135	151	189
M28	95	229	169	190	198	196	212	210	210	228	229	219	253	160	154	81	144	174	205	211	138	154	196
M29	118	283	305	231	241	238	259	259	255	276	281	276	311	197	191	103	176	211	250	263	171	185	242
M30	128	296	219	241	249	256	275	271	277	294	297	300	329	199	192	110	192	229	270	282	187	195	261
M32	110	251	187	205	211	219	235	231	239	253	255	256	283	170	165	96	165	197	234	242	161	170	223
M33	130	297	217	240	250	253	274	272	275	291	298	297	329	200	194	113	191	226	269	281	187	193	260
M34	123	279	204	226	236	236	258	257	257	274	281	277	309	189	182	108	179	213	253	265	176	184	245
M35	104	238	174	193	203	203	220	221	221	238	244	234	267	161	155	90	155	185	218	229	152	159	211
A37	182	372	274	294	306	325	343	334	351	363	368	388	429	246	240	139	242	289	341	360	242	241	333
A38	181	372	270	294	306	323	341	334	346	362	368	386	429	246	257	137	288	285	336	358	239	239	332
A39	171	362	261	288	300	311	329	328	333	350	355	370	413	245	256	133	230	273	323	346	279	234	321
A40	177	369	272	291	302	322	340	331	348	359	366	384	424	245	256	136	238	287	338	356	238	287	330
A41	102	254	173	205	216	197	227	229	219	241	247	246	273	177	188	87	149	176	210	221	144	158	206
A42	102	262	183	213	226	203	235	241	227	246	256	254	277	182	193	88	154	183	217	230	150	165	214
A43	46	115	73	90	99	82	100	105	95	107	112	102	114	181	192	38	62	73	88	91	58	70	85
M44	57	152	109	121	127	127	134	134	135	141	144	143	161	105	116	54	91	108	128	130	86	99	116
M45	36	122	82	99	104	90	105	108	99	110	115	107	117	85	96	40	65	77	93	95	59	75	86
A46	51	146	103	118	123	116	129	130	126	135	139	136	149	103	114	51	85	100	118	121	79	94	111
M47	24	77	55	66	68	62	71	74	69	75	79	71	80	56	67	27	45	53	63	65	41	52	58
M48	24	77	56	67	71	62	72	75	69	76	80	71	83	57	68	27	45	54	64	66	41	53	59
M49	6	39	26	32	35	30	35	38	35	40	42	33	40	28	39	15	23	27	33	33	21	27	30
M50	37	87	58	73	77	64	79	82	74	85	88	79	89	63	74	30	50	58	70	72	46	50	67
A51	91	245	171	198	207	193	220	231	212	229	236	235	259	170	181	85	144	173	201	213	137	153	197

TABLE I. - CONTINUED

PART 3.- TEMPERATURE RISE ABOVE AMBIENT-AIR TEMPERATURE AT STATIONS 40.5 AND 44.5, °F

Thermocouple No. \ Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
M52	147	306	227	246	256	268	283	279	288	301	306	316	351	209	194	116	199	237	278	290	196	202	268
M54	136	269	199	215	221	235	250	246	255	269	272	277	306	182	176	101	176	211	251	255	172	178	237
M55	153	315	234	256	265	276	295	290	299	314	319	330	356	213	198	116	203	244	289	301	200	205	278
M56	135	290	211	235	244	251	269	264	271	286	286	297	331	201	196	106	187	224	265	270	183	191	249
M57	107	257	185	208	216	216	235	231	232	249	251	257	284	177	171	91	159	190	225	231	154	167	214
M59	170	335	245	270	282	293	310	306	313	330	337	348	388	231	225	124	217	258	305	314	216	221	299
M61	118	251	186	205	213	215	232	227	234	248	249	257	282	174	170	195	161	192	227	232	159	166	214

PART 4.- TEMPERATURE RISE ABOVE AMBIENT-AIR TEMPERATURE AT STATION 52, °F

Thermocouple No. \ Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
M62	44	85	55	71	74	63	78	79	73	83	86	72	87	61	55	29	49	58	72	72	45	56	64
M63	52	93	60	78	82	71	87	86	81	91	93	84	97	67	61	31	54	61	75	75	49	59	70
M64	47	107	69	87	91	78	98	99	91	105	108	87	109	76	68	35	64	77	93	90	58	72	84
M65	43	107	70	88	91	78	99	99	92	107	111	87	109	79	69	36	66	80	97	95	64	74	85
M66	52	120	80	97	102	92	109	108	104	115	117	108	122	84	77	38	67	80	97	96	63	74	88
M67	62	135	93	109	114	107	124	122	119	131	134	123	142	95	87	46	82	97	116	116	77	88	107
M68	47	122	82	100	104	93	114	114	109	123	127	105	128	90	80	43	77	93	111	90	71	85	99
M69	54	139	97	114	117	112	130	128	127	140	143	127	150	100	88	48	90	107	128	123	84	97	115
M70	90	202	147	167	171	172	190	185	188	202	203	197	224	142	134	76	130	156	186	184	123	136	169
M71	109	234	176	193	197	206	220	213	224	236	236	240	265	163	157	91	157	186	220	218	150	162	199
M72	44	125	87	104	108	98	118	118	114	128	131	111	132	90	82	45	80	96	115	113	74	88	103
M73	84	195	144	162	166	167	182	179	182	195	196	191	216	138	131	73	125	151	178	176	119	134	162
M74	52	136	97	114	116	112	129	126	127	139	139	127	148	97	89	49	88	105	126	121	81	95	109
M75	40	112	81	96	99	90	108	106	105	117	118	102	121	83	75	44	72	87	104	100	66	80	90
M76	65	152	112	127	130	128	143	139	141	153	153	143	168	90	101	59	98	116	138	135	93	107	124
M77	36	94	67	81	83	77	89	89	87	95	97	86	96	69	72	35	60	71	83	82	54	67	73
M78	38	74	48	61	64	54	68	68	64	73	75	63	75	54	48	29	43	50	60	61	41	49	55
A79	53	112	75	94	99	84	104	105	98	110	113	105	117	84	78	41	66	76	90	94	61	73	87
M80	11	24	25	26	27	31	35	38	44	48	45	40	135	25	26	15	26	31	38	33	22	31	32

TABLE I. - CONTINUED

PART 5.- TEMPERATURE RISE ABOVE AMBIENT-AIR TEMPERATURE AT STATIONS 104.5 and 112, °F.

Thermo-couple No. \ Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
M81	85	96	63	77	80	74	84	84	81	89	91	86	98	65	59	30	52	62	77	78	48	60	67
S82	85	73	47	58	60	59	65	64	64	69	70	66	75	48	45	27	41	47	56	60	38	46	51
M83	112	127	82	99	102	96	110	110	107	117	120	116	146	85	80	41	72	84	101	104	67	82	95
S84	112	104	62	76	77	77	87	84	88	94	96	92	131	63	59	32	60	68	83	88	56	69	81
M85	151	275	190	220	230	223	250	249	246	266	264	276	312	191	184	92	166	197	235	248	161	177	228
M86	146	246	165	194	203	195	224	222	219	240	248	246	287	169	160	77	148	173	207	218	143	159	200
M87	147	232	155	187	195	182	210	209	208	214	232	230	260	163	156	77	139	162	194	204	132	148	186
S88	142	177	105	138	142	131	161	159	171	181	182	183	204	114	98	59	106	124	151	164	104	115	146
M89	162	285	198	230	240	232	258	257	258	274	183	286	317	197	187	100	173	207	247	260	168	182	237
M90	154	269	185	214	225	219	243	241	242	260	266	268	303	185	176	91	164	193	231	244	160	172	223
M91	163	299	211	241	251	248	272	270	270	289	297	301	335	207	198	104	184	218	261	274	180	192	252
S92	151	208	143	177	188	176	196	201	188	216	221	214	235	155	82	74	127	154	187	196	125	136	186
M93	158	277	195	223	232	231	249	248	249	266	274	277	306	189	166	97	167	201	240	251	163	175	230
M95	153	292	209	235	244	246	263	262	262	278	288	292	323	199	189	102	177	213	255	266	174	187	242
M96	146	271	193	216	225	227	242	240	242		265	269	297	183	172	95	162	196	235	244	157	170	221
M97	150	276	196	223	231	231	245	245	245	260	269	273	300	190	175	96	166	199	238	249	161	176	226
S98	115	164	115	128	127	143	141	139	149	151	155	160	181	107	82	56	98	119	142	146	92	104	128
M99	151	296	113	238	245	250	266	264	266	281	291	296	326	202	192	103	180	218	259	270	174	188	243
M100	142	274	195	218	224	231	243	239	244	257	267	270	298	183	174	95	164	199	238	247	158	173	221
M101	137	253	182	201	204	216	221	217	226	234	239	249	274	169	156	88	150	182	218	226	145	160	200
M102	128		164	183	187	196	204	199	207	216	219	222	244	154	145	79	135	165	197	199	129	148	179
M103	107	183	133	149	152	156	167	163	166	176	179	177	198	124	115	61	109	132	159	160	102	121	141
M104	77	128	92	104	105	110	116	112	115	123	124	118	133	87	78	43	76	92	111	109	69	87	95
M105	128	219	163	177	181	195	200	195	205	214	215	220	240	150	141	78	135	165	196	197	129	147	176
M106	68	122	87	99	99	102	110	108	109	117	118	111	123	83	72	40	71	87	106	103	64	83	87
M107	131	233	172	190	192	205	211	206	216	224	225	232	251	157	149	83	143	173	206	206	134	155	183
M108	107	190	139	152	153	169	171	164	173	181	181	184	203	124	115	65	113	140	168	165	106	125	141
M109	72	127	90	101	102	109	113	109	113	120	120	115	130	85	73	41	73	91	109	105	66	85	87
M110	107	173	126	136	137	156	147	144	153	151	156	162	182	114	103	60	100	124	149	148	93	113	123
S111	89	117	92	81	80	128	91	86	116	98	96	116	136	64	51	40	73	89	107	110	62	81	74
S112	72	89	66	68	68	89	76	73	81	80	81	83	93	57	50	32	52	63	75	76	47	60	60
M113	51	81	56	65	65	67	73	70	71	75	78	75	79	54	48	27	44	53	65	64	38	53	60
M114	54	60	41	48	50	51	53	53	50	55	58	51	57	41	37	20	33	40	48	49	31	40	41
A115	191	360	263	286	300	315	327	325	335	351	356	371	413	243	236	131	230	275	327	344	230	232	317
A116	189	353	255	281	294	304	319	319	325	344	347	361	401	239	241	130	224	267	315	335	224	228	308
A117	186	357	249	283	297	311	322	328	328	346	351	366	406	241	243	130	226	273	322	342	227	229	312
A118	186	335	239	266	280	282	301	301	303	320	327	336	368	226	211	118	205	247	294	310	204	212	285
A119	177	161	108	130	137	123	143	144	138	·149	155	150	166	112	104	52	90	107	128	133	85	101	120
A120	113	166	121	130	135	145	143	144	143	149	155	154	171	111	100	55	94	115	138	138	86	105	120
M121	143	255	192	208	214	228	236	232	241	252	255	263	288	178	172	94	162	194	231	235	155	172	210
M123	142	261	195	212	217	234	240	234	244	256	258	266	290	181	174	94	164	199	237	237	157	175	211
M124	134	233	179	192	194	218	239	209	224	232	231	242	263	160	151	87	147	180	215	211	141	160	187

TABLE I.– CONCLUDED

PART 6.– TEMPERATURE RISE ABOVE AMBIENT-AIR TEMPERATURE AT STATIONS 314.5 AND 322, °F

Thermocouple No. \ Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
S125	94	–	30	50	52	50	56	55	53	58	60	54	61	43	35	20	34	39	46	48	31	40	41
S126	138	–	104	120	125	115	140	135	140	149	147	149	171	105	61	53	92	107	128	134	87	101	128
S127	138	–	112	128	135	134	145	145	149	154	159	159	176	110	40	54	93	118	140	147	89	103	125
S128	130	–	119	125	130	143	142	139	149	153	151	161	180	99	60	56	96	115	134	141	89	105	114
M130	137	–	134	162	172	150	179	181	174	189	194	190	213	140	117	65	112	134	161	167	105	125	148
M131	146	–	150	177	187	172	196	197	190	206	211	210	231	155	120	72	125	149	178	187	117	138	165
M132	151	–	168	196	207	196	216	217	210	225	232	231	254	168	131	79	139	166	199	207	131	151	185
M135	137	–	153	169	176	178	188	187	187	196	199	207	226	141	115	71	121	147	177	182	114	133	154
M136	144	–	174	203	214	199	224	227	217	236	242	239	263	175	163	85	145	174	207	215	137	158	193
M137	107	–	101	117	123	115	128	128	124	239	138	133	148	101	86	48	81	177	116	118	75	92	100
M138	120	–	128	147	154	148	162	162	158	170	174	173	191	127	112	63	106	126	151	155	99	117	134
M139	108	–	115	131	136	131	144	144	139	150	154	152	170	111	95	54	92	110	131	135	86	103	116
A140	171	–	230	256	268	272	290	289	294	308	313	321	354	215	208	115	199	238	280	296	194	205	271
A141	166	–	220	246	258	257	277	277	277	293	298	304	335	210	201	109	188	226	267	279	185	196	255
A142	168	–	224	249	262	264	282	282	284	298	304	311	343	211	201	110	191	228	270	285	185	198	260
A143	165	–	209	236	248	241	263	265	262	277	284	187	314	200	180	101	174	209	250	261	168	184	236
A144	107	–	79	103	110	87	207	111	94	109	115	103	114	90	75	37	62	72	87	88	55	74	77
M146	135	–	158	183	192	183	204	204	200	214	221	220	240	157	144	78	132	159	189	196	126	144	176
M147	139	–	178	203	212	207	227	227	224	238	246	247	270	174	164	86	149	180	216	223	143	161	198

Figure 1.– The cargo airplane equipped with a thermal ice–prevention system.

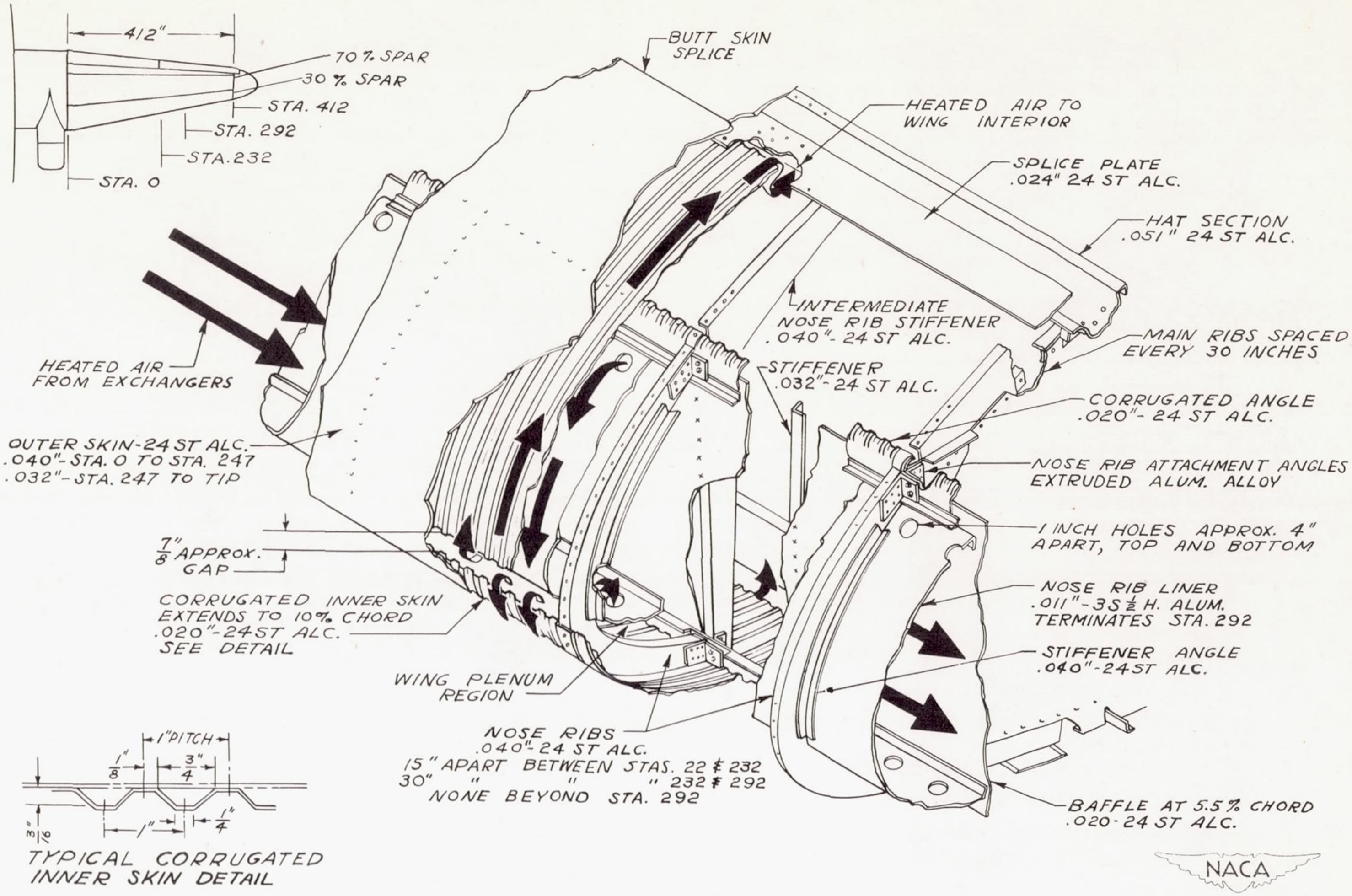


FIGURE 2.- TYPICAL OUTER WING-PANEL LEADING-EDGE SECTION AS REVISED FOR THERMAL ICE-PREVENTION

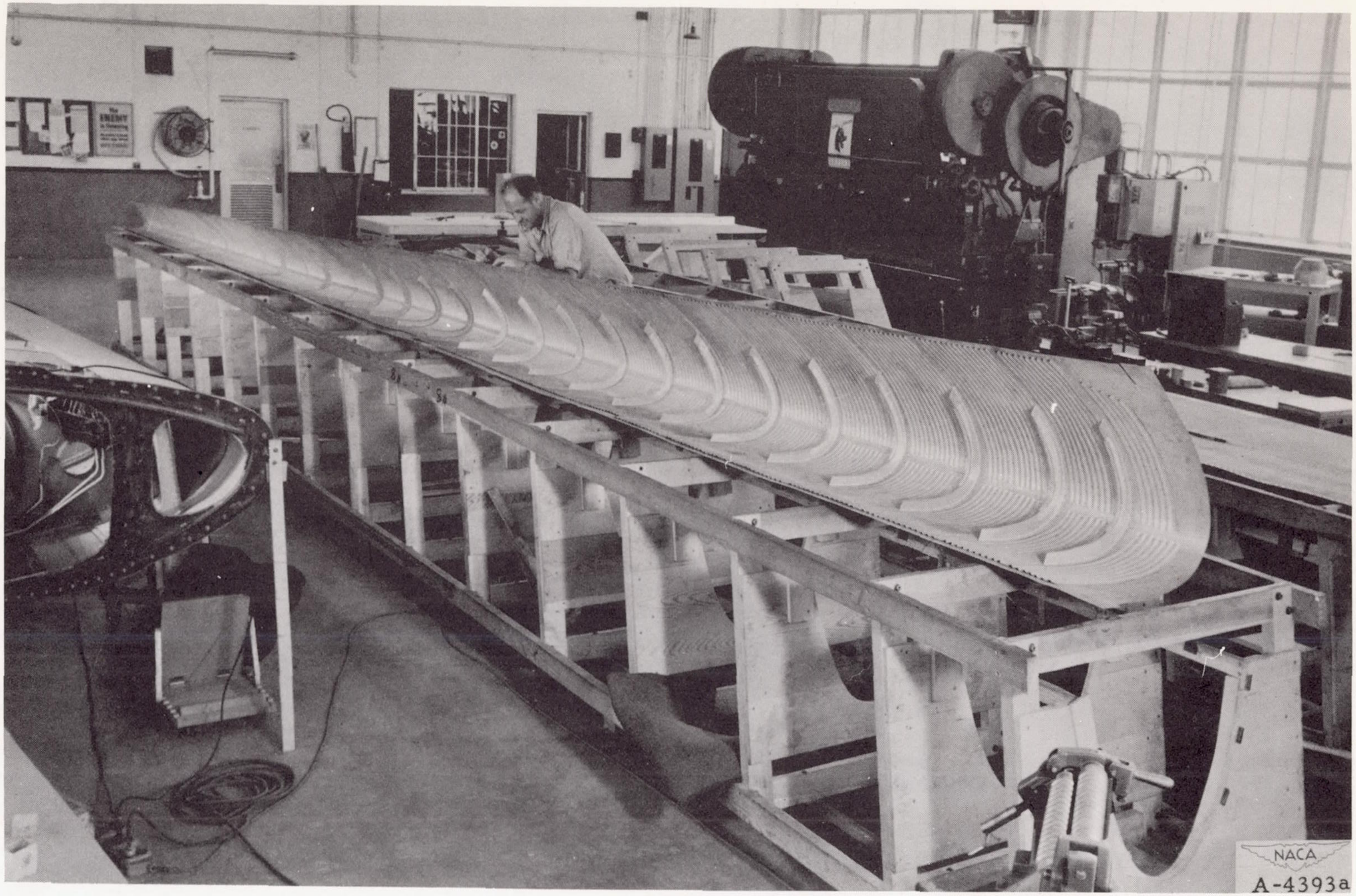


Figure 3.— Corrugated inner skin and revised nose ribs installed in leading edge of the left wing outer panel of the cargo airplane.

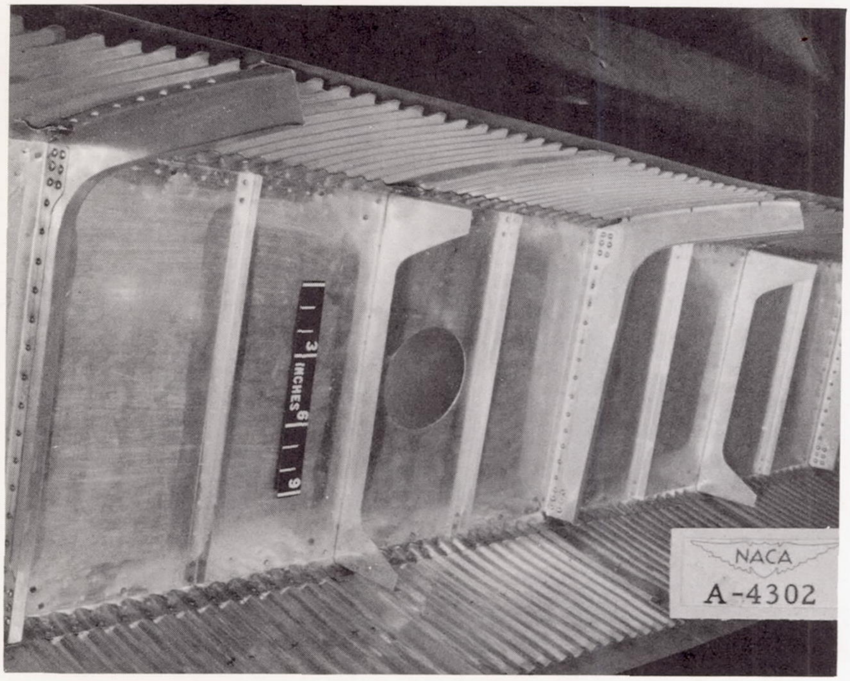


Figure 4.- Rear view of 5.5-percent-chord baffle plate installed in wing outer-panel leading edge of the cargo airplane.

Figure 5.– Nose liner in right-wing outer-panel leading edge viewed from inboard end.

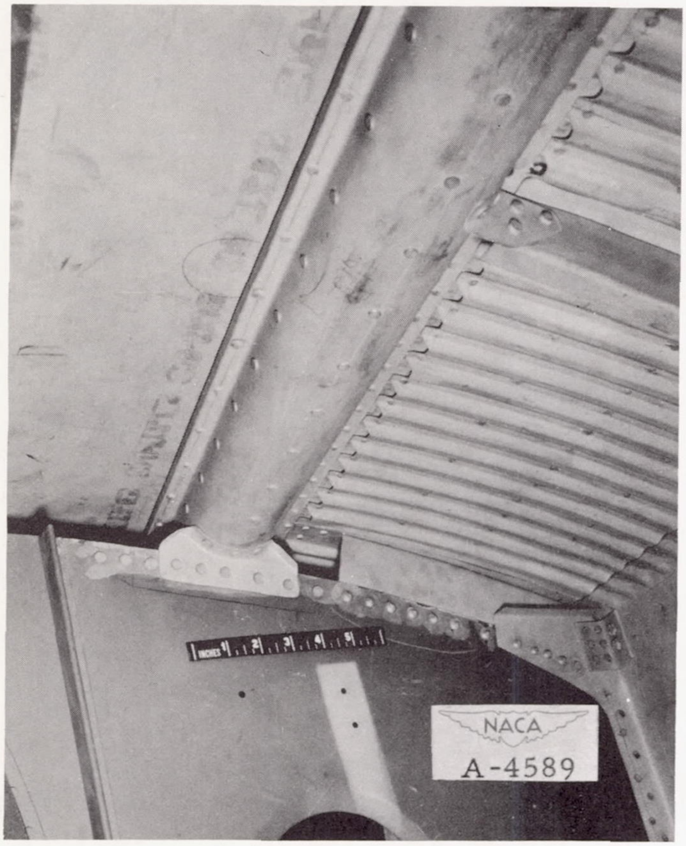


Figure 6. – Typical details of attachment of revised wing outer–panel leading edge to original structure.

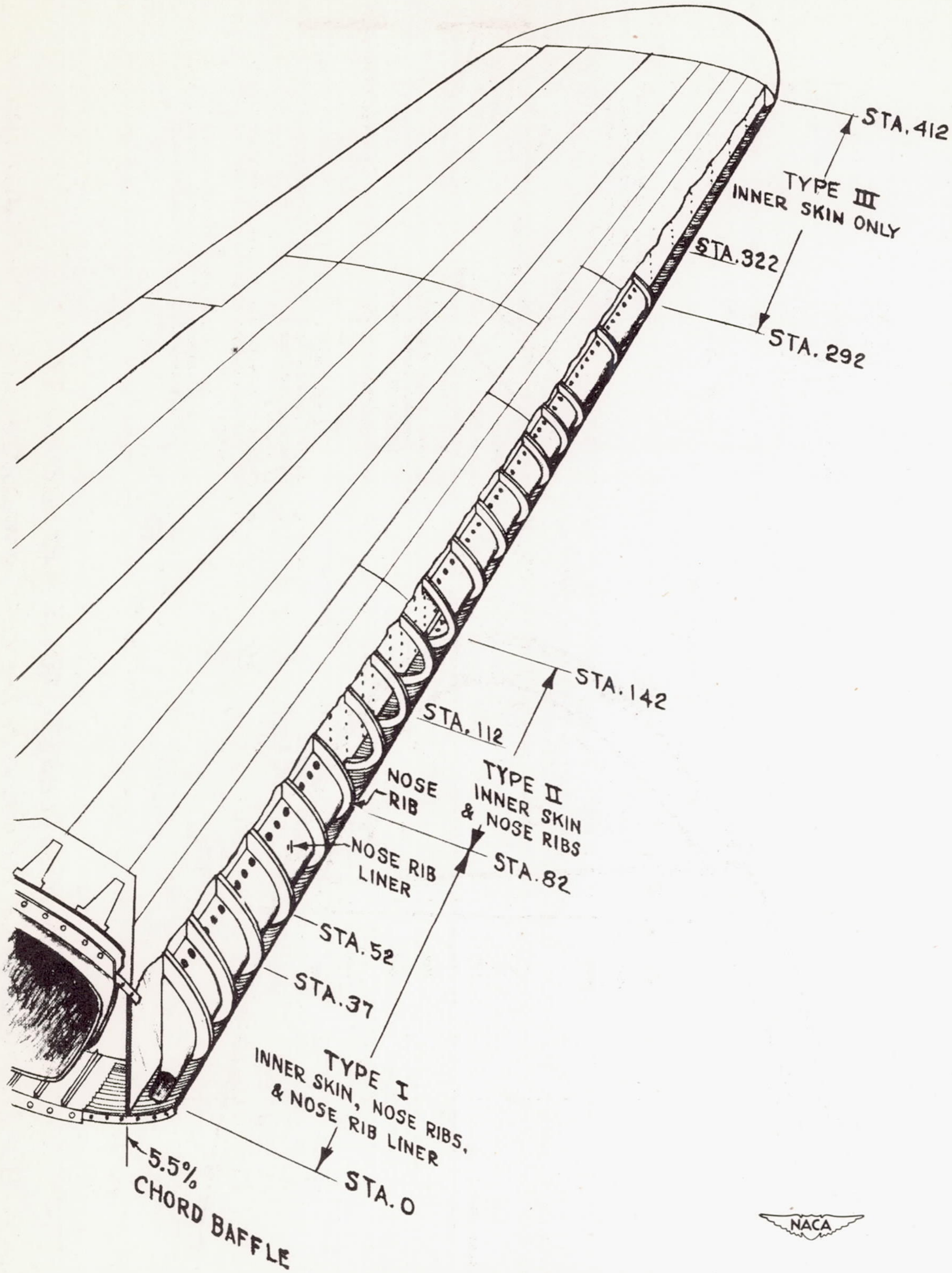
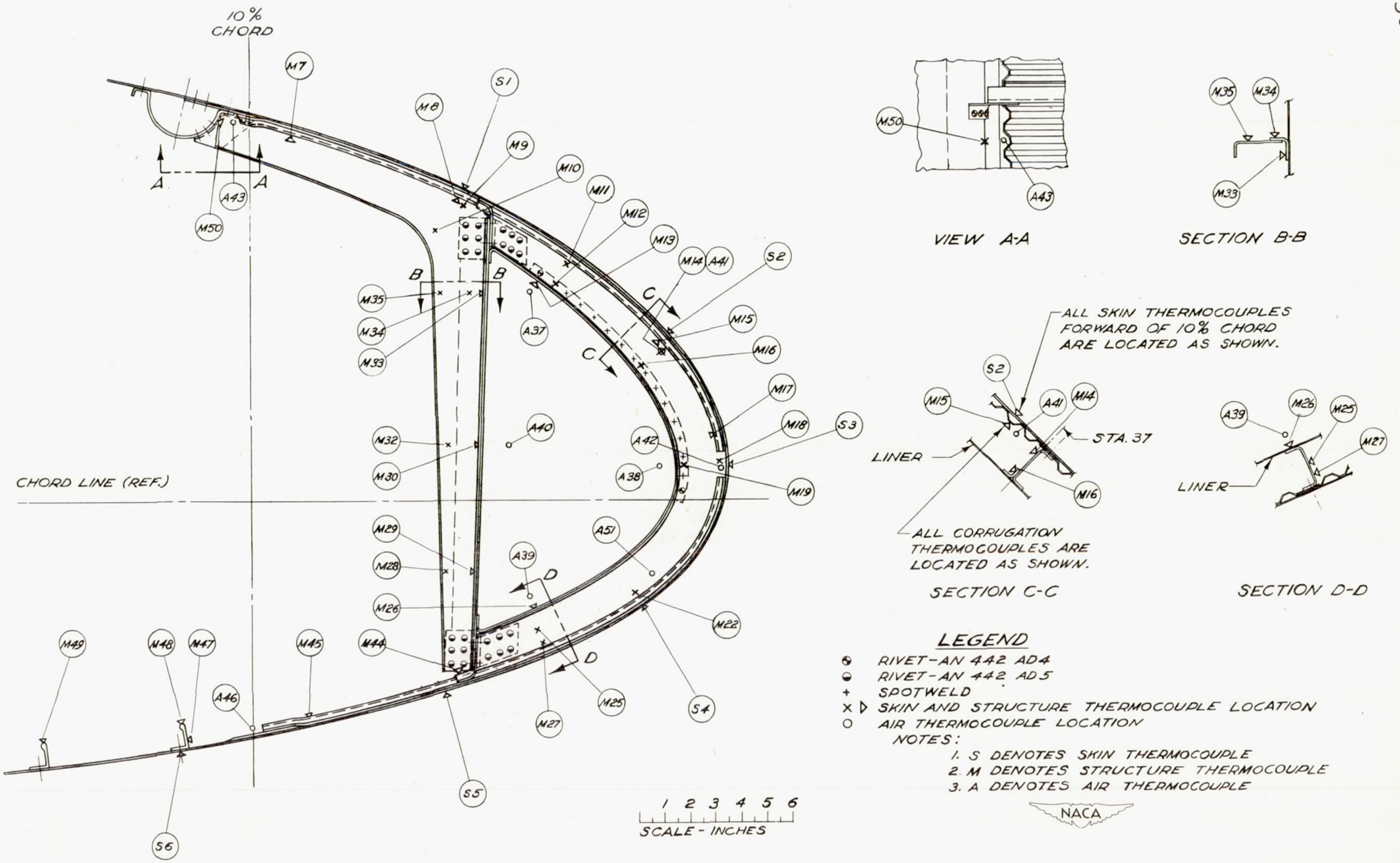


FIGURE 7.- LOCATION AND GENERAL INTERNAL DESIGN OF THE THREE TYPES OF LEADING EDGES TESTED IN THE OUTER WING PANEL.



LEGEND

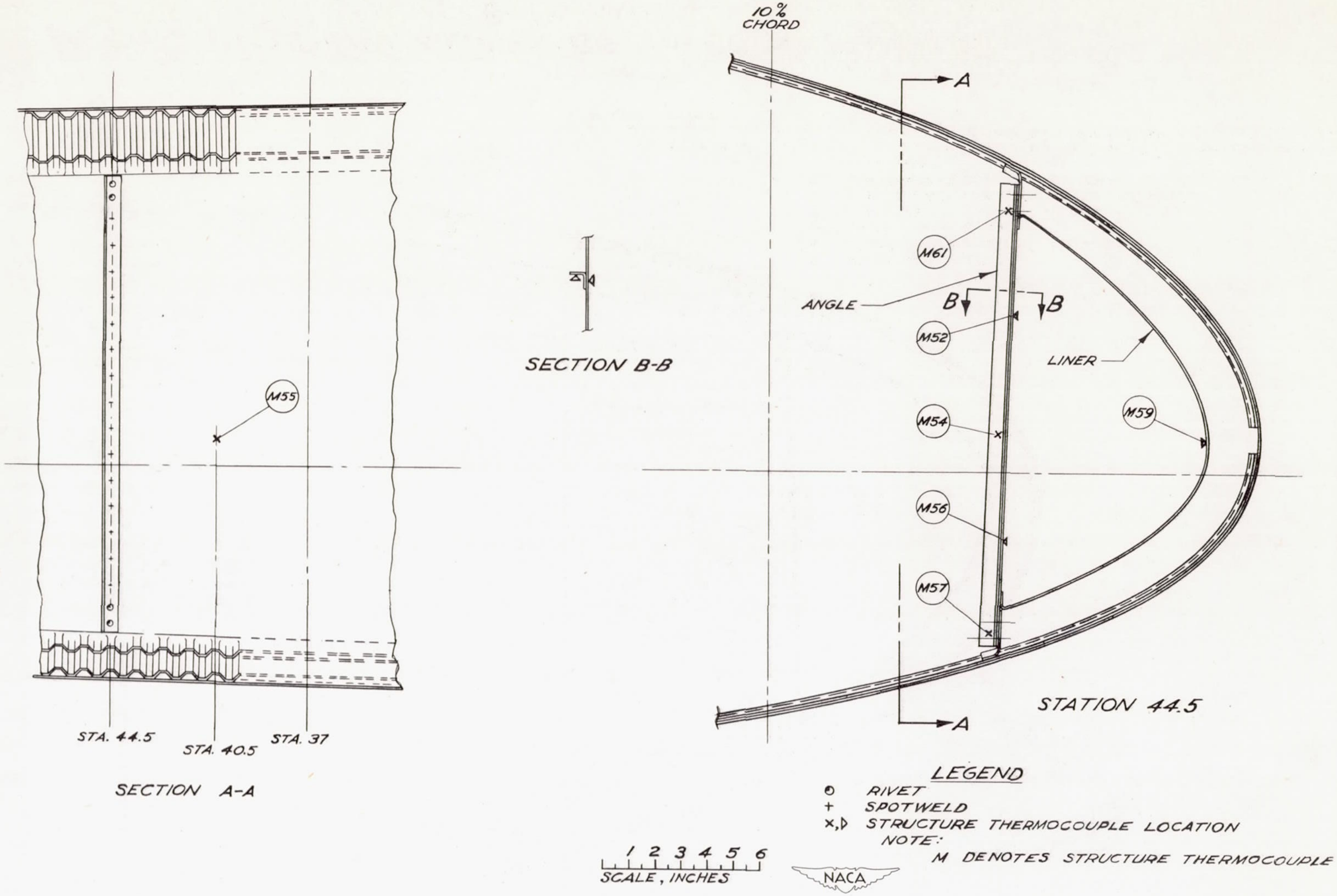
- ⊗ RIVET–AN 442 AD4
- ◒ RIVET–AN 442 AD5
- \+ SPOTWELD
- × ▷ SKIN AND STRUCTURE THERMOCOUPLE LOCATION
- ○ AIR THERMOCOUPLE LOCATION

NOTES:

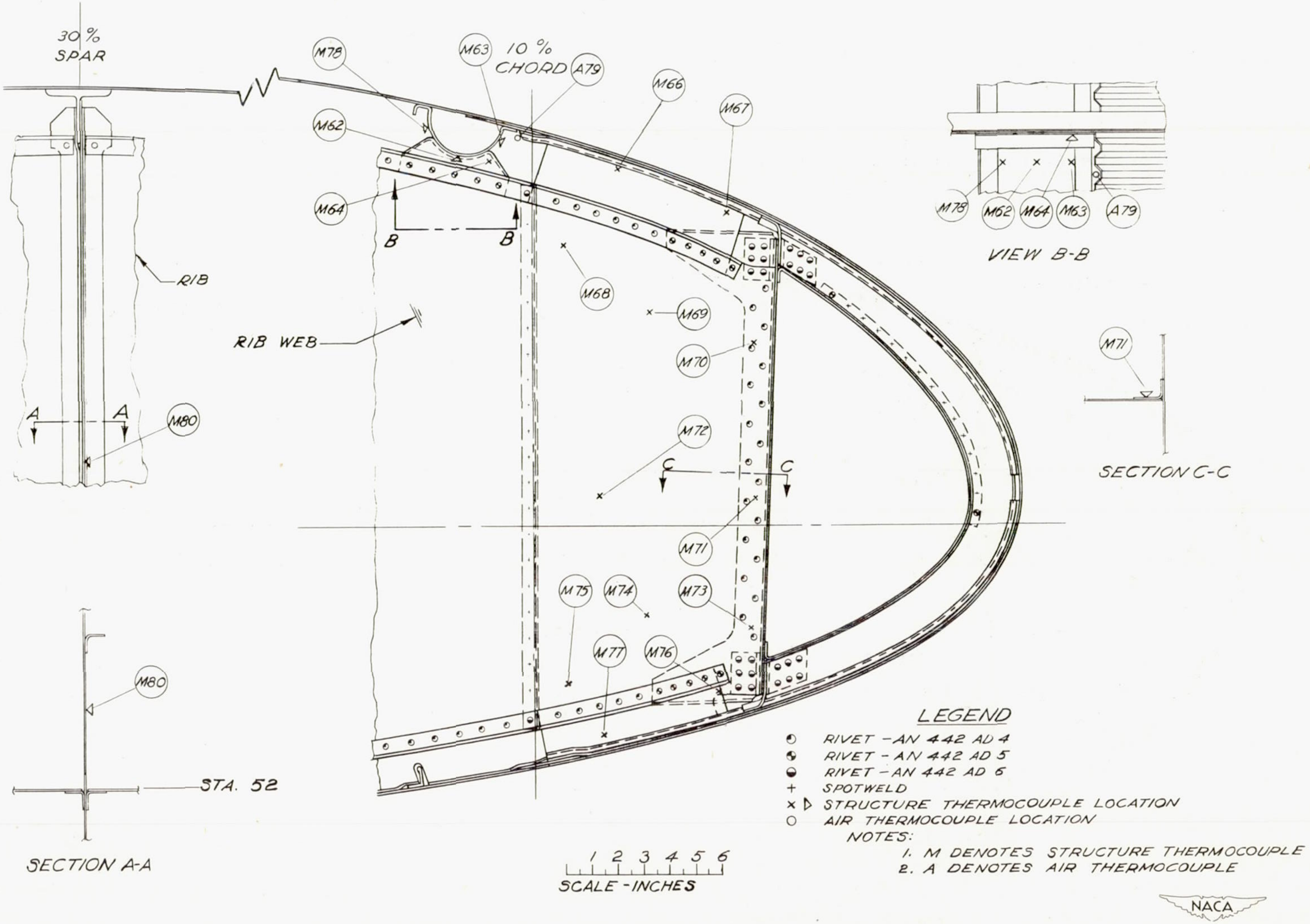
1. S DENOTES SKIN THERMOCOUPLE
2. M DENOTES STRUCTURE THERMOCOUPLE
3. A DENOTES AIR THERMOCOUPLE

(a) THERMOCOUPLES 1 TO 51 AT STATION 37.

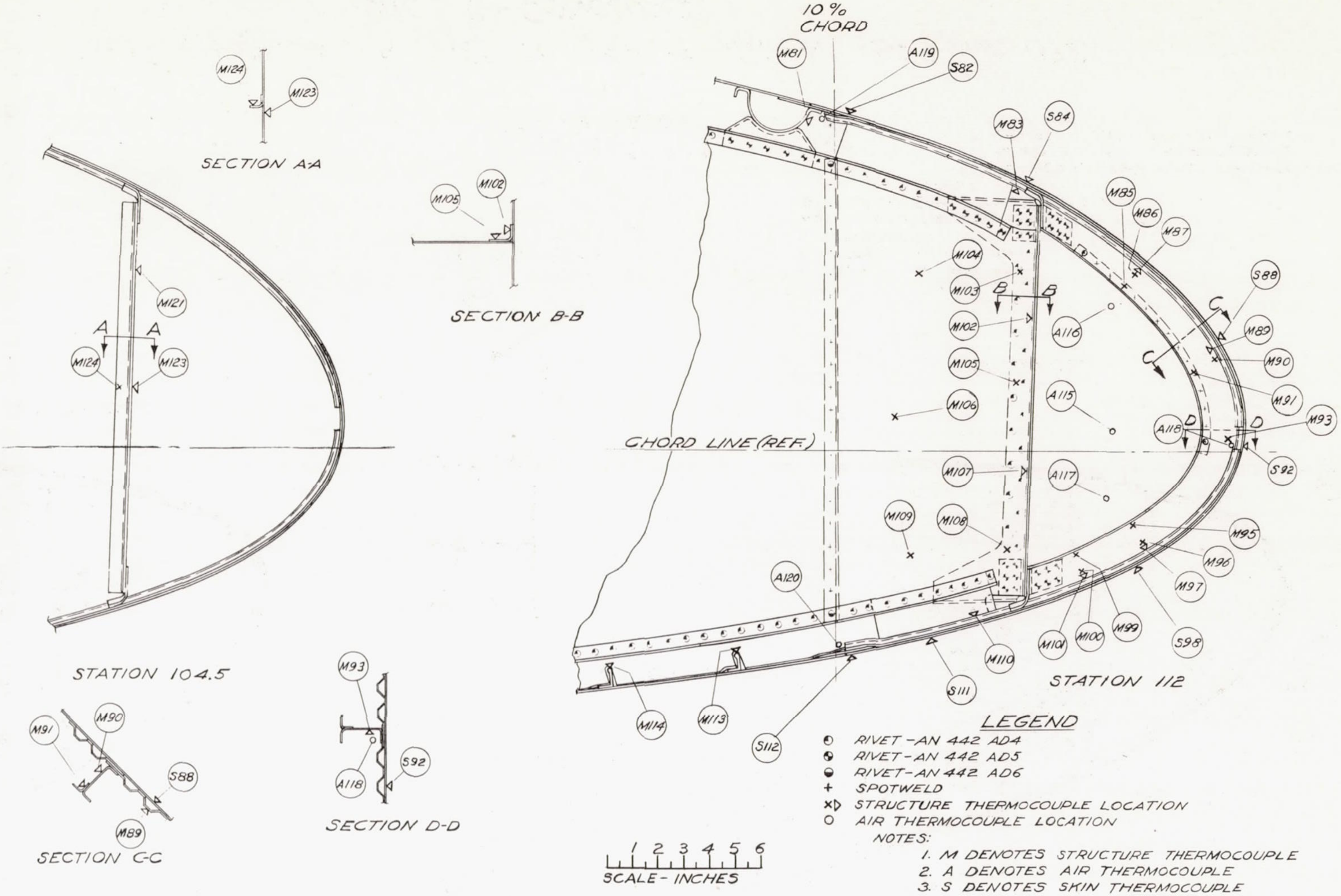
FIGURE 8.– THERMOCOUPLE LOCATIONS IN THE LEFT WING OUTER PANEL OF THE CARGO AIRPLANE.



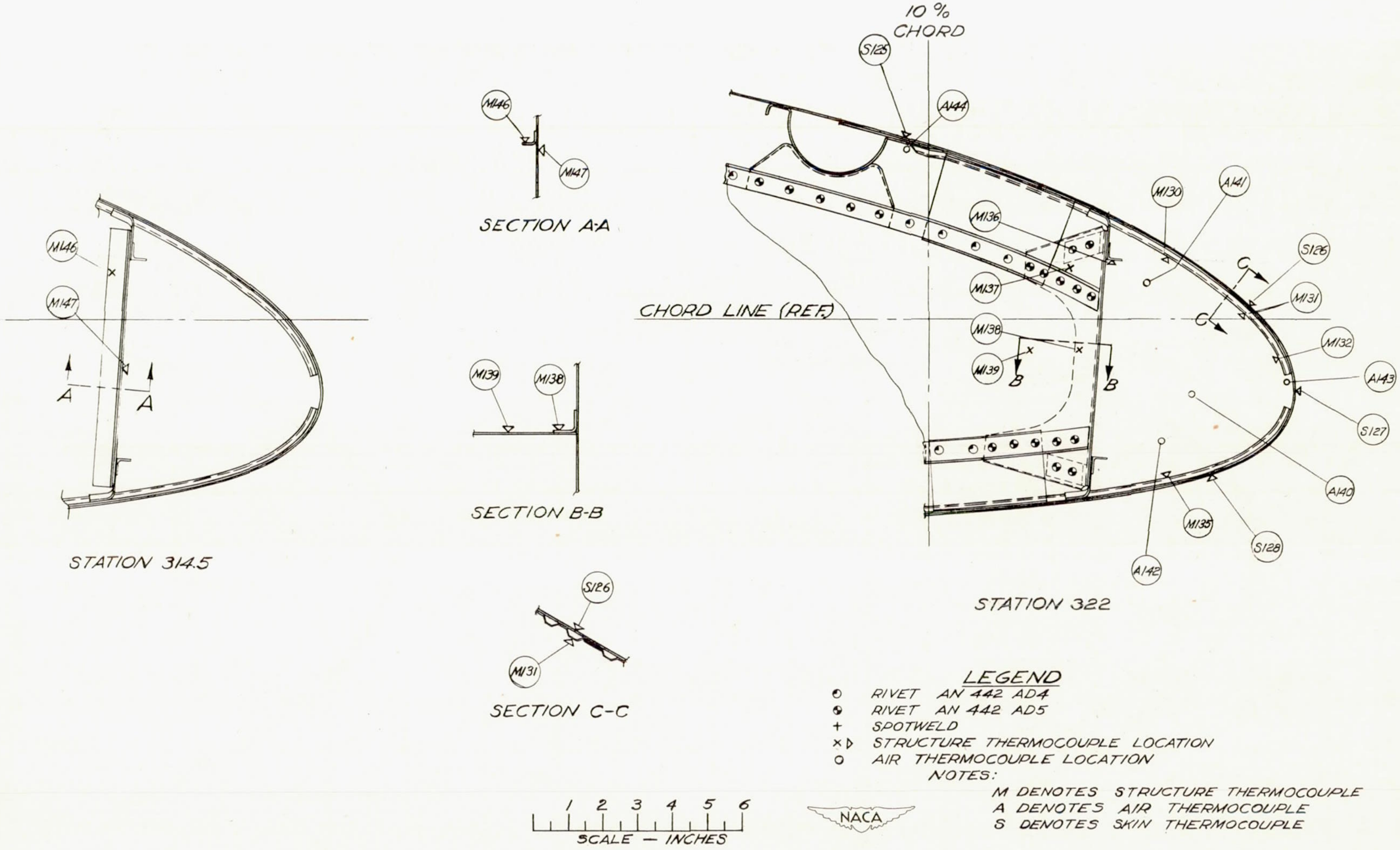
(b) THERMOCOUPLES 52 TO 61 AT STATIONS 40.5 AND 44.5
FIGURE 8.- CONTINUED.



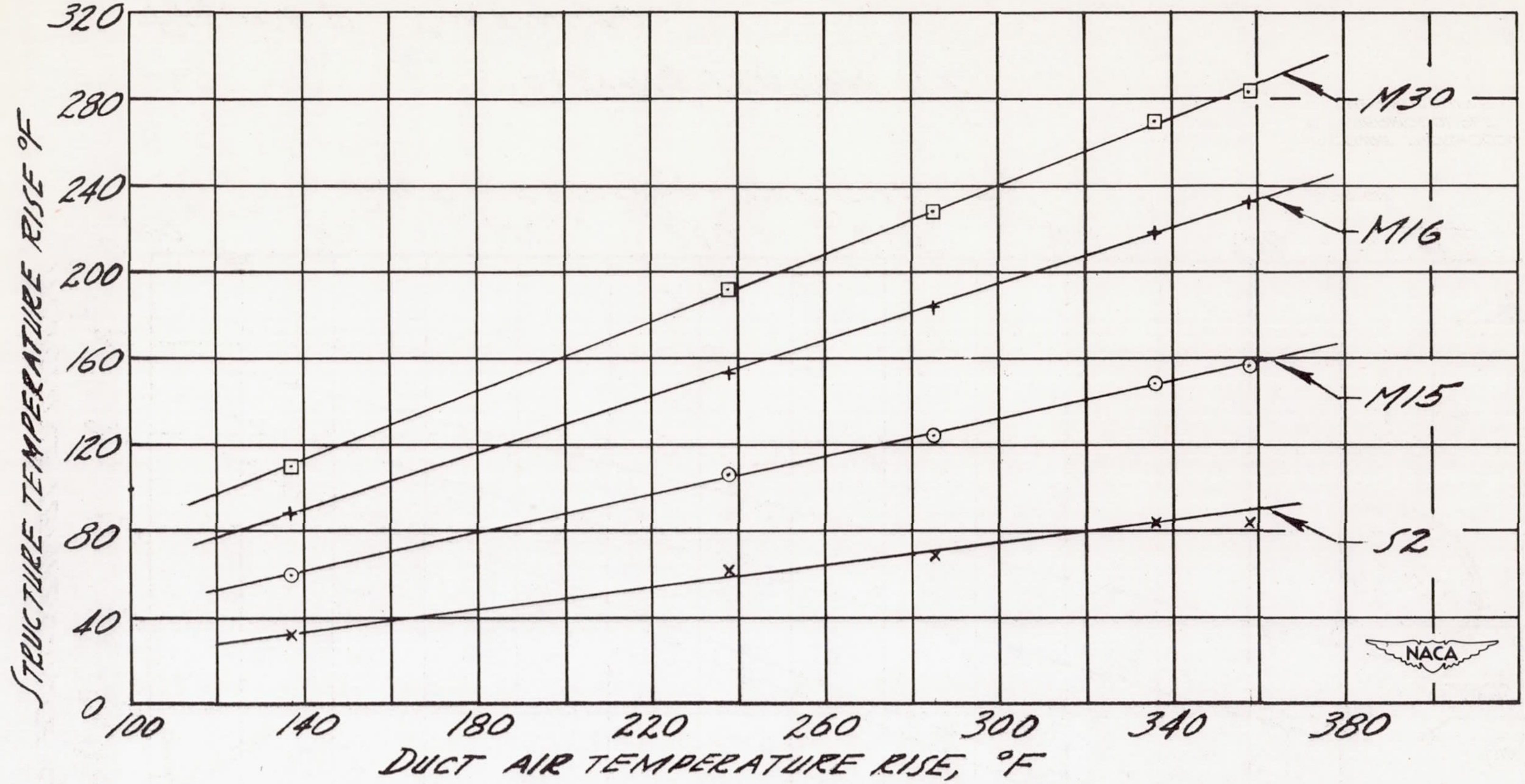
(c) THERMOCOUPLES 62 TO 80 AT STATION 52.
FIGURE 8.- CONTINUED.



(d) THERMOCOUPLES 81 TO 124 AT STATIONS 104.5 AND 112.
FIGURE 8.- CONTINUED.

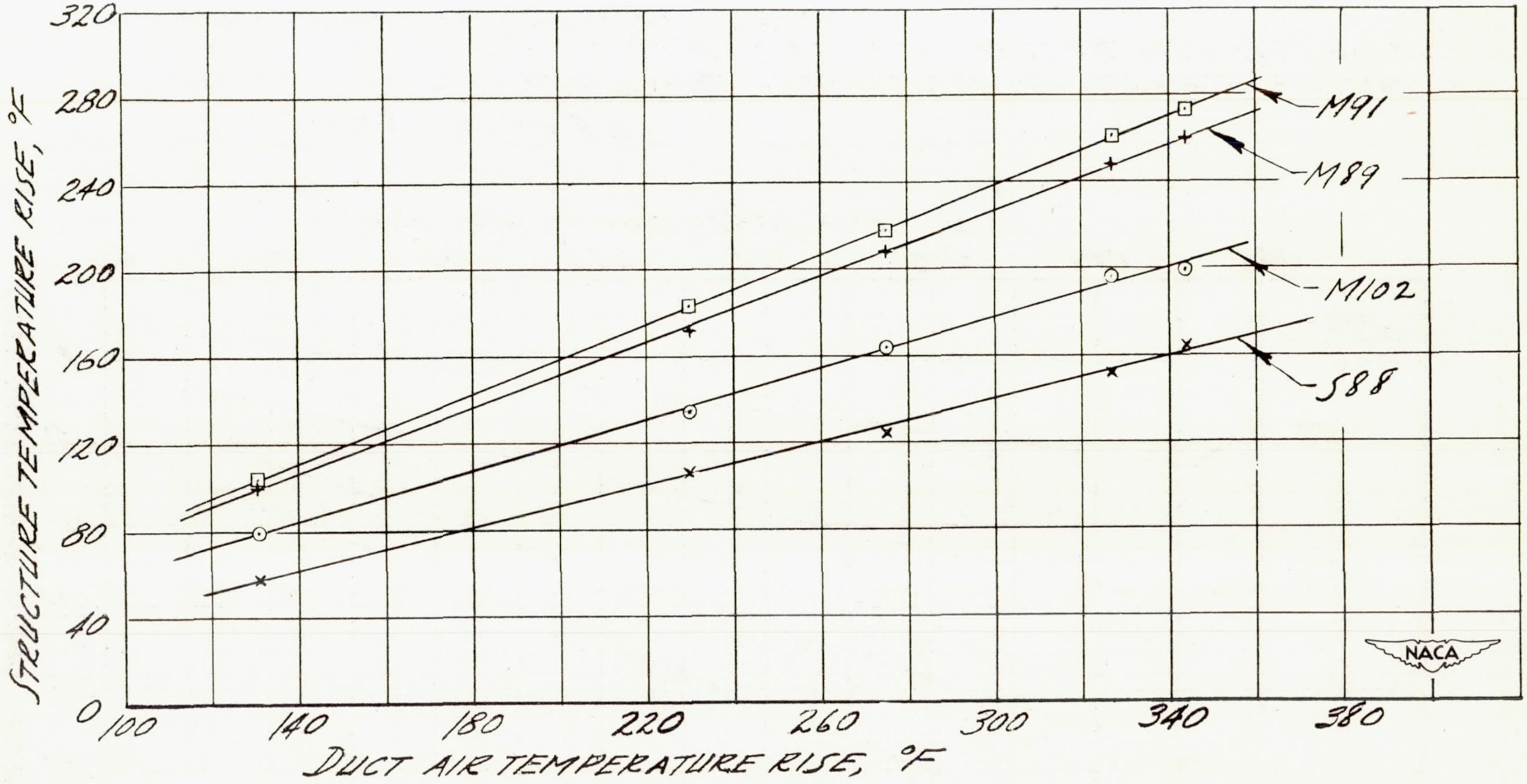


(e) THERMOCOUPLES 125 TO 147 AT STATION 314.5 AND 322.
FIGURE 8.- CONCLUDED.



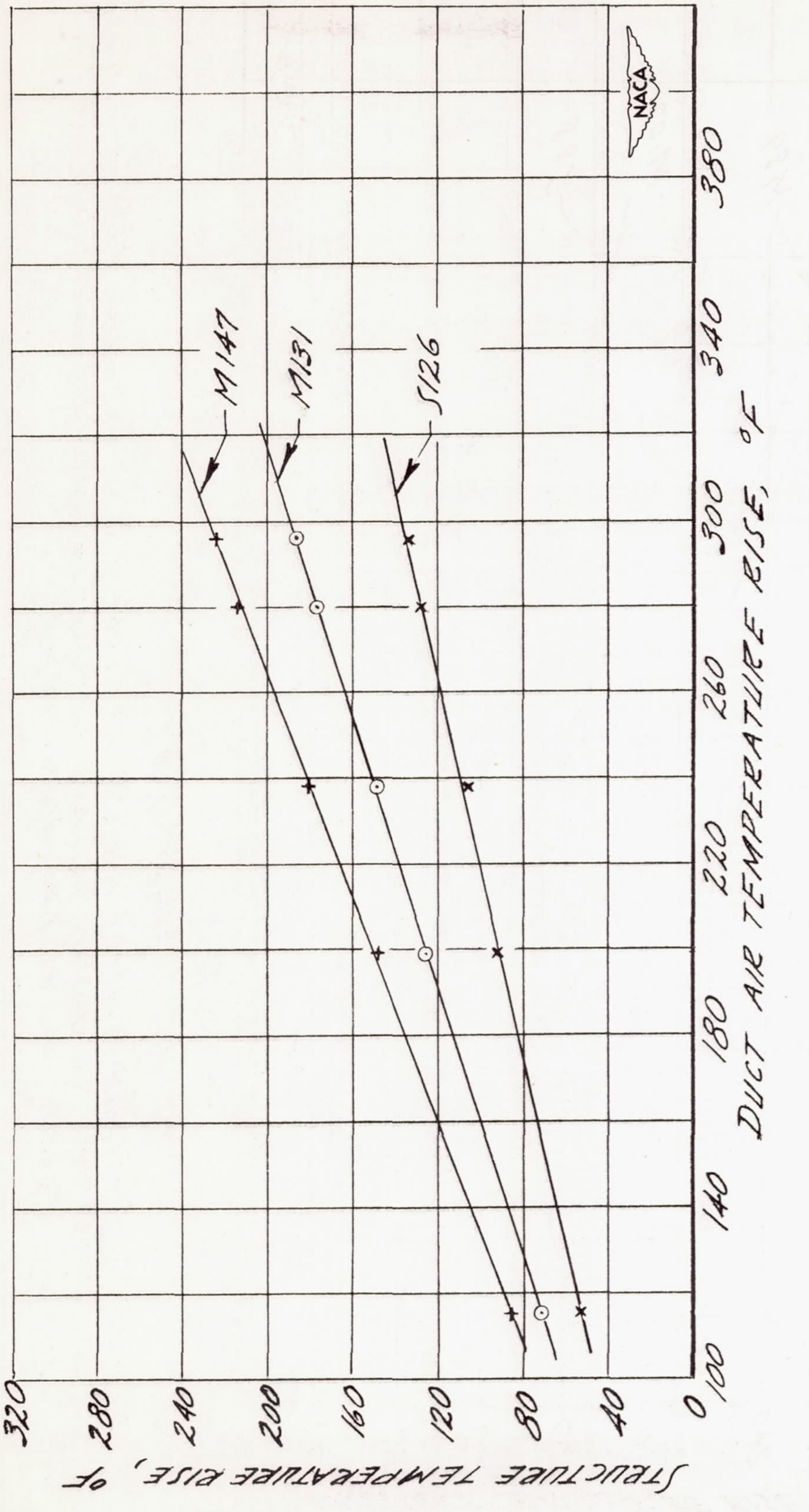
(a) WING STATION 37.

FIGURE 9. - STRUCTURE TEMPERATURE RISE AS A FUNCTION OF DUCT AIR TEMPERATURE RISE AT VARIOUS THERMOCOUPLE LOCATIONS. AIRPLANE INDICATED AIRSPEED, 136 MPH; PRESSURE ALTITUDE, 10,000 FEET; AIR FLOW RATE, 3600 LB /HR



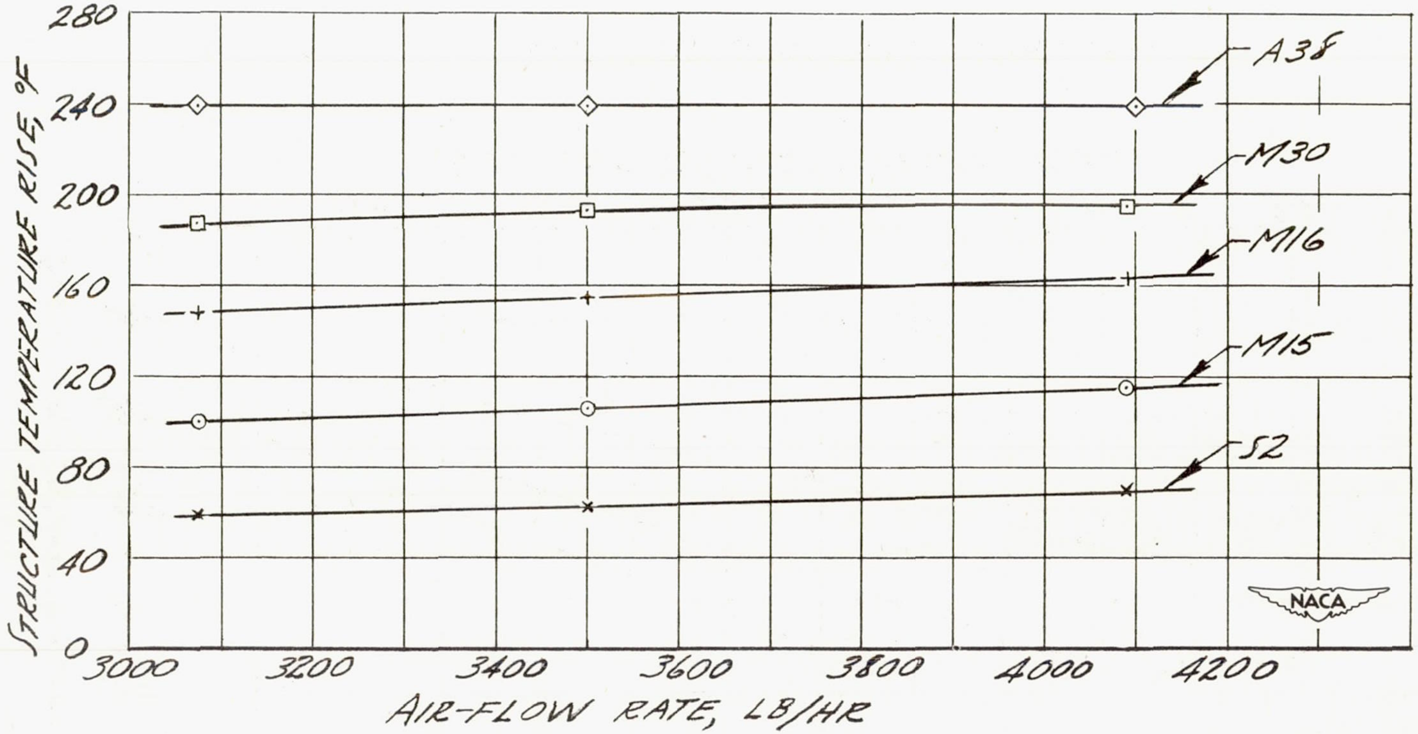
(b) WING STATION 112

FIGURE 9. - CONTINUED



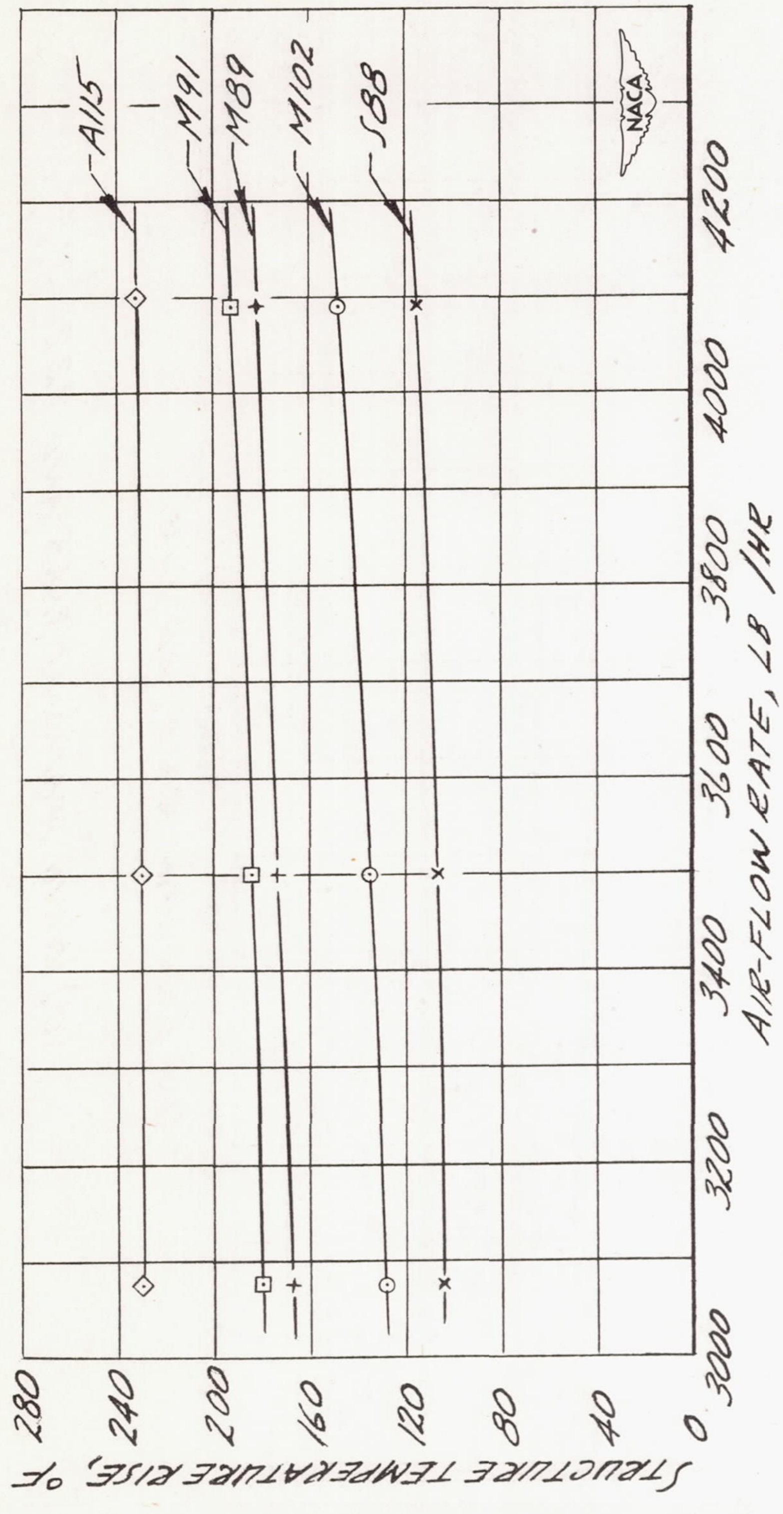
(c) WING STATIONS 314.5 AND 322

FIGURE 9. - CONCLUDED



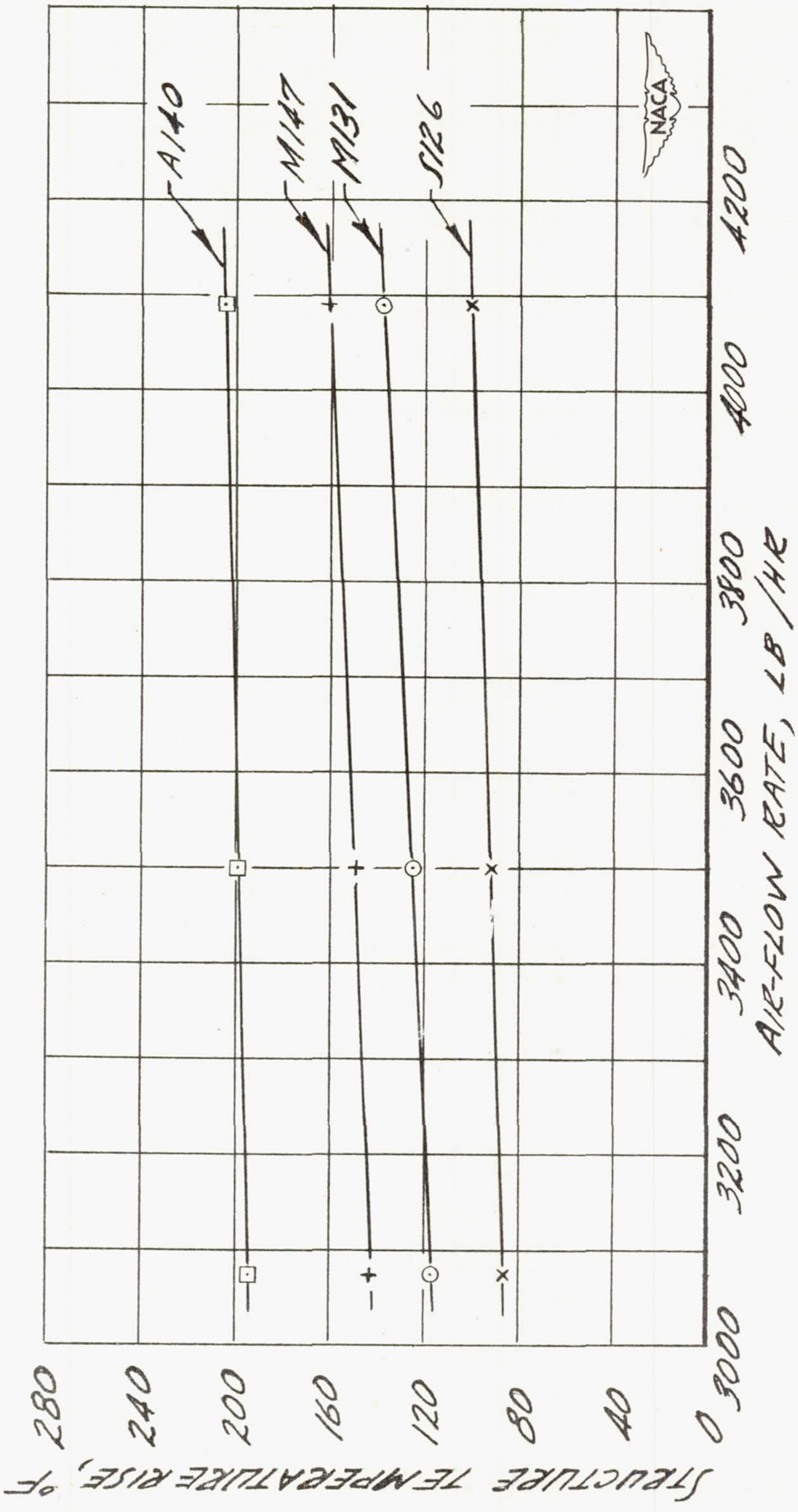
(a) WING STATION 37

FIGURE 10.- STRUCTURE TEMPERATURE RISE AS A FUNCTION OF AIR-FLOW RATE AT VARIOUS THERMOCOUPLE LOCATIONS. AIRPLANE INDICATED AIRSPEED, 135 MPH; PRESSURE ALTITUDE, 10,000 FT; HEATED-AIR TEMPERATURE, 304° F



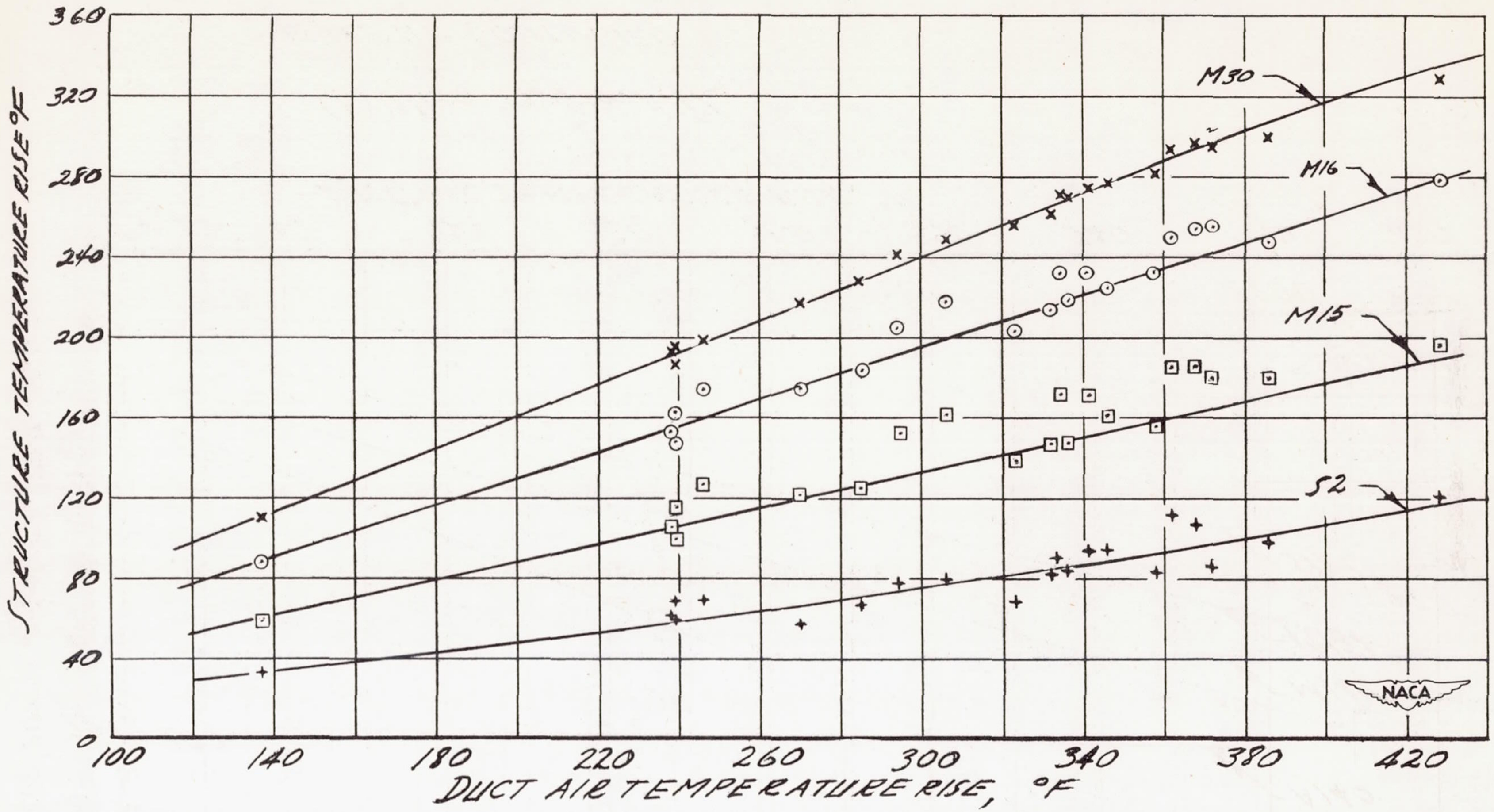
(b) Wing station 112

Figure 10.- Continued



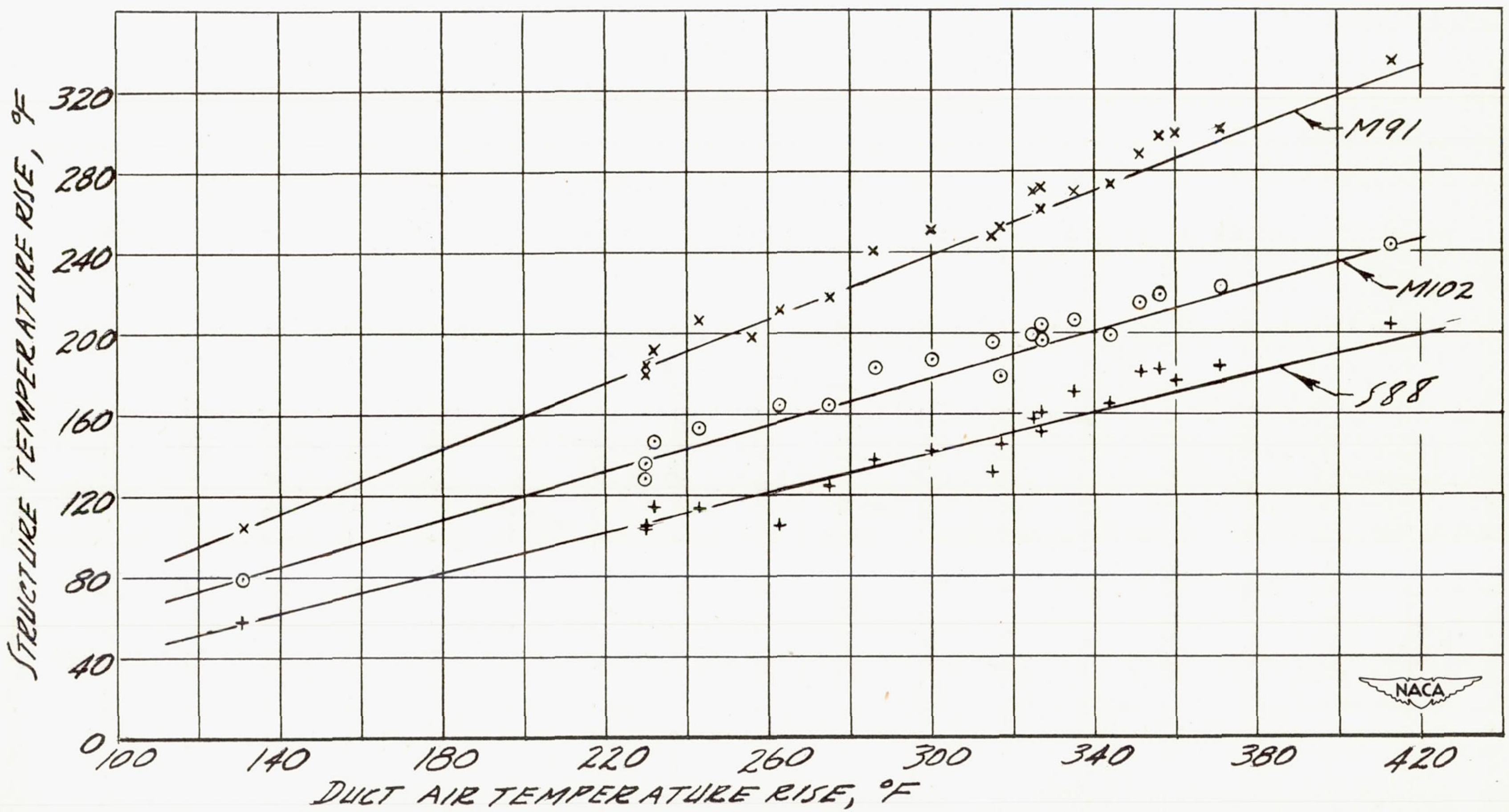
(c) WING STATIONS 314.5 AND 322

FIGURE 10.- CONCLUDED



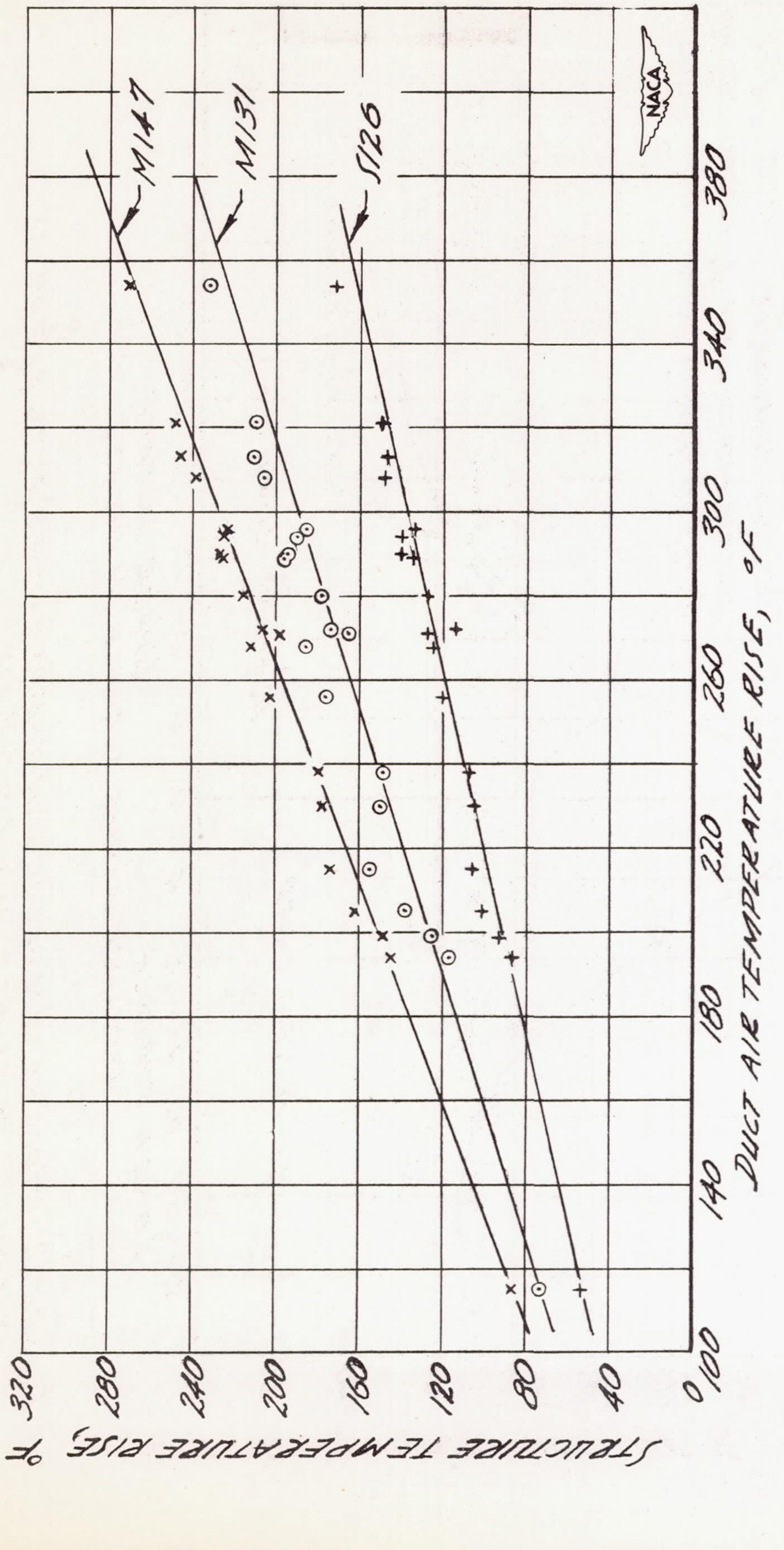
(a) WING STATION 37

FIGURE 11.- STRUCTURE TEMPERATURE RISE AS A FUNCTION OF DUCT AIR TEMPERATURE RISE AT VARIOUS THERMOCOUPLE LOCATIONS FOR ALL TEST CONDITIONS EXCEPT TEST NUMBERS 1 AND 15.



(b) Wing station 112

Figure 11.- Continued



(c) Wing stations 314.5 and 322

Figure 11.- Concluded

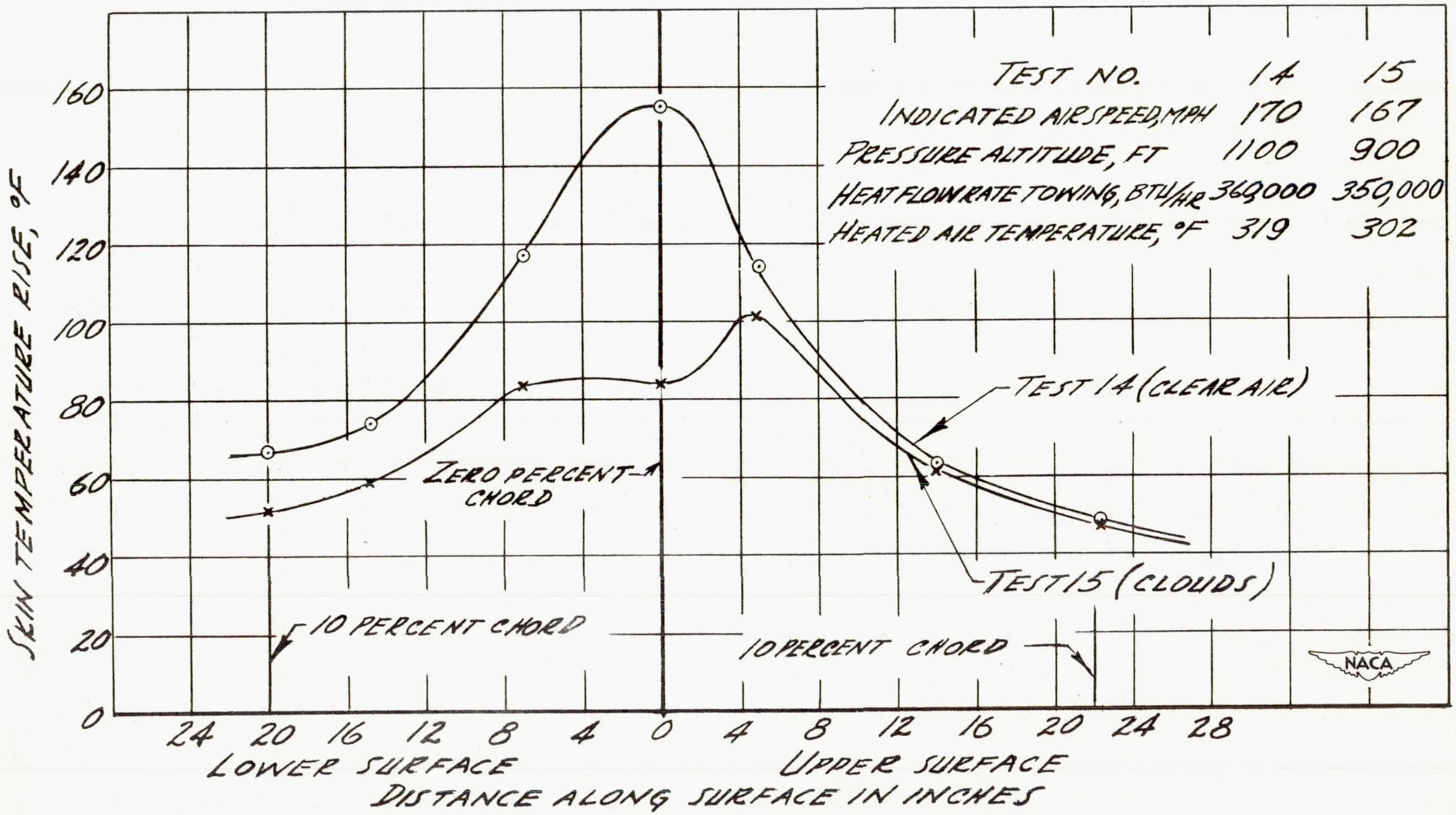


FIGURE 12.- WING LEADING-EDGE SKIN-TEMPERATURE DISTRIBUTION AT STATION 112 IN CLOUDS AND IN CLEAR AIR.