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THE BRAZING OF ALUMINUM
BRONZE TO INCONEL
SECOND INTERIM REPORT

to
OAK RIDGE NATIONAL LABORATORY

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by
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SUMMARY

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It is demonstrated that aluminum-bronze can be brazed to Inconel with nickel-base filler metal in a hydrogen atmosphere without flux in spite of the unfavorable thermodynamics. This necessitates hydrogen of a high degree of purity and a rapid heating rate in bringing the work to brazing temperature.

In brazing an actual heat exchanger, neither of these conditions is readily fulfilled, since the size of the unit makes for a slow heating rate and its complexity, combined with the fact that oxygen is liberated by the dissociation of the oxide film on the Inconel, leads to local contamination of the atmosphere. Laboratory experiments with tube-and-fin specimens designed to simulate these conditions result as expected in failure to braze.

These adverse conditions can be overcome by the use of a suitable flux in conjunction with the dry hydrogen atmosphere. Borate-base fluxes are effective but are considered undesirable on the basis of low solubility and consequent risk of corrosion failures in service.

Fluxes based on mixed halides are found to be successful in promoting brazing. Since such fluxes are more readily soluble they are not expected to contribute a corrosion hazard. A preferred mixture is 5 parts NaCl, 2 parts LiCl and 1 part CuCl. With this flux, smoothly-filleted joints are obtained exhibiting adequate penetration into the crevice.

A mechanism by which the halide-base flux operates is proposed on a thermodynamic basis. This mechanism is somewhat tentative in nature pending further experimental work but depends

on decreasing the activity of oxygen in the flux and of aluminum in the bronze sufficiently that the product $a_{Al}^2 \cdot a_O^3$ does not exceed the deoxidation constant for the oxidation of the aluminum.

Additional experimental work is indicated and should be directed toward brazing in the absence of flux with filler metal containing a small lithium addition, toward experiments to determine the optimum composition of the halide-base flux, and toward evaluation of the resistance to high-temperature attack of brazed joints prepared by the various successful procedures.

INTRODUCTION

The first experiments in this investigation into the brazing of aluminum bronze fins to Inconel tubes using nickel-base filler metal demonstrated that, in a dry hydrogen atmosphere, joining took place only where the filler metal had been pre-placed. Apparently the Al_2O_3 coating on the bronze prevented the bronze metal from flowing, a fact which was consistent with thermodynamic calculations of the oxidation reactions. These aspects of the work were described in the first Progress Report ("The Brazing of Aluminum Bronze to Inconel," February 13, 1956). Also demonstrated was the effectiveness of borate-base fluxes in promoting brazing and the lack of success when $CuCl$, NH_4Cl or iodine was attempted as a flux. All experiments were with T-type specimens.

The work to be described in the present report has been along the following directions:

1. Brazing tube-and-fin specimens in dry hydrogen. This

was successful if a rapid heating rate was used.

2. Devising a test which would simulate the longer heating times necessary for brazing the actual heat-exchangers. Two suitable tests, differing in their degree of severity, were developed in which the aluminum bronze could not be wet by the filler metal in dry hydrogen.
3. Investigation of a variety of materials as fluxes to overcome the conditions developed in the tests above.
4. Investigation of halide flux formulations to perform the same function.
5. Modification of successful halide flux formulations toward lower volatility to prepare for the possibility of dip brazing.

EXPERIMENTAL

Specimen Materials

The use of the T-joint type of specimen, the preparation of which was described in the First Progress Report, was continued. Fig. 1 is a photograph of such a specimen. The aluminum bronze panel (supported by an Inconel back-up panel) formed the bar of the T, with an Inconel panel as the upright. The brazing metal used was CM53 powder.

A second type of specimen was prepared from $1\frac{1}{2}$ " lengths of $3/16$ " O.D. Inconel tubing, and fins of 5% aluminum bronze sheet, 0.016" thick, with $3/16$ " diameter punched holes. For these tube-and-fin specimens, pre-formed $\frac{1}{4}$ "

sintered rings of CM52 or CM53 braze metal were slipped over the Inconel tubing. Fig. 2 shows such a specimen, on which the filler metal ring has been placed only on the lower joint.

Regarding the various salts used as flux ingredients, it should be recorded that not all salts were perfectly dry. In fact in some instances, for reasons of expediency, salts with water of crystallization were used.

Apparatus

The vertical tube furnace described in the first Progress Report was used for all the runs. Fig. 3 is a schematic diagram of this equipment.

Test Procedure

Four test procedures, designated A,B,C and D , were employed in the course of this investigation. The T-specimen test described in the first report has been modified slightly (Test A). A similar procedure was followed with the tube-and-fin specimens (Test B). In addition two new tests were devised with the tube-and-fin specimens to simulate the slower heating rates resulting from the larger size of the heat exchanger as compared to the small laboratory specimens (Tests C & D).

Test A: T-specimen.

1. A saddle of 0.010" Inconel sheet was attached to the center of the Inconel panel, as shown in Fig. 1, to act as a support or dam for the braze metal powder. The metal powder was poured into the pocket so formed.
2. When flux was to be used, the customary procedure was to grind and mix the flux ingredients dry in a

Fig. 1. Photograph of T-specimen.

Fig. 2. Photograph of tube-and-fin specimen.

Fig. 3. Schematic diagram of vertical tube furnace.

mortar and pestle, wet them with acetone and apply the resultant slurry along the T-joint and to the small heap of metal powder. It was necessary to work as quickly as possible to minimize the amount of moisture absorbed by the salts which in many cases were deliquescent.

3. The specimen was immediately attached to the Nichrome suspension wire in the vertical tube furnace and raised enough to be in a warm zone to facilitate the removal of the acetone and of the greater part of any absorbed moisture. The specimen remained in this drying zone for 10 minutes in dry hydrogen flowing at 300 ml/min.
4. The hydrogen flow rate was increased to 500 ml/min. and the specimen rapidly raised to the center of the furnace where the temperature was 1375°F. The temperature of the specimen was measured with an optical pyrometer and the behaviour of the flux observed through a sight glass. The specimen appeared to reach the brazing temperature in approximately two minutes.
5. After six minutes the specimen was rapidly lowered to the cooling zone and subsequently removed from the furnace.

Test B: Tube-and-fin specimen.

The procedure in this test was very similar to that of Test A except that a three-minute test time was used instead of six minutes. The specimen was less massive and reached brazing temperature in about 1½ minutes. It was

not necessary to provide a dam for the filler metal since this was applied as a preformed ring. When no flux was used no drying was required and the specimen was raised directly to the hot zone without the preheat in the warm zone.

The extent of penetration of the filler metal into the crevice formed between the Inconel tube and the bronze fin was evaluated by examination of metallographic sections.

Test C: Tube-and-fin specimen with high-temperature preheat.

1. The tube-and-fin specimen with a ring of CM53 on the bottom joint only, as in Fig. 2, was raised to brazing temperature as usual but held at temperature for 10 rather than for 3 minutes to permit the oxide layer on the upper bronze fin to thicken.
2. The specimen was cooled in hydrogen and a ring of CM53 filler metal set at the upper joint. If flux was to be used this was applied to the upper joint as a slurry in acetone (as described under Test A).
3. If flux had been used, the acetone and moisture was dried off by holding for 10 minutes in the warm zone toward the bottom of the furnace tube. The specimen was raised to brazing temperature, hold for three minutes, lowered to the cooling zone, and removed.

Test D: Tube-and-fin specimen with high-temperature preheat wrapped in Inconel foil.

1. To simulate the more severely oxidizing conditions in

the inner recesses of the heat exchanger where the partial pressure of oxygen is high due to the dissociation of the Cr_2O_3 film on the Inconel tubes, Test C was modified by wrapping the tube-and-fin specimen in Inconel foil. A 4" x 4" square of 0.002" Inconel was torch-annealed in air and wrapped around the tube-and-fin specimen having a CM53 filler metal ring on the lower joint only.

2. The wrapped specimen was hung in the furnace tube, the furnace sealed and the system evacuated to remove air trapped inside the Inconel foil. Hydrogen was then admitted to a pressure of one atmosphere and flowed at 500 ml/minute. The specimen was raised to brazing temperature, held for 10 minutes, and cooled.
3. The Inconel foil was removed, a CM53 ring and flux applied at the upper joint and the specimen wrapped in a second piece of oxidized Inconel foil.
4. As before, this was sealed into the furnace tube and the system evacuated to remove the enclosed air and also to dry out the acetone and moisture from the flux. Hydrogen was admitted to one atmosphere, flowed at 500 ml/minute, the specimen raised to brazing temperature, held for four minutes, and cooled.

Brazing Experiments

The brazing experiments have been tabulated in groups in such a way as to facilitate interpretation.

For reasons of clarity one experiment may appear in more than one group and not all the experiments are reported. A full listing of the tests may be found in the appendix (Table VII). The twelve experiments from the first report have been included in the tables to make the presentation more complete.

Table I summarizes the experiments dealing with brazing in dry hydrogen without the use of flux. Brazing temperature was 1375°F; the time of the runs with T-specimens was six minutes and with tube-and-fin specimens, three minutes.

In Run 76 a copper panel was substituted for aluminum bronze in order to observe the effect of the complete absence of an Al_2O_3 film. Experiment 78 (also 68 and 77) was an attempt to achieve this same condition by a preliminary treatment to de-aluminize the surface layer of the bronze panel; the bronze was heated in air at 850°F for six minutes and the resulting grey oxide film removed by pickling in NaOH solution.

Experiments 43 and 44 (also 45, 46 and 47) were attempts to observe the effect of a lithium addition to filler metal. No nickel-base brazing alloy containing lithium was available but a copper-silver eutectic alloy containing 0.5% lithium was obtained and used in Run 44. Run 43 with Easy Flo 45 brazing alloy was run as a control since this alloy is similar in composition but contains no lithium.

TABLE I

BRAZING EXPERIMENTS IN DRY HYDROGEN WITHOUT FLUX

Run No.	Specimen Type	Braze Metal	Experiment Type	Remarks
2	T	CM52	A	Brazing at limited areas
13	Tube & Fin	CM52 & 53	B	Good joint. Flowed into crevice.
14 ^(a)	" " "	"	B	Mixture of Cl ₂ & H ₂ gas. Fair joint. Poor penetration into crevice.
20 ^(c)	" " "	CM53	C ^(b)	No joining. Bronze not wet.
21 ^(c)	" " "	"	B	Partly brazed.
22	" " "	"	C	Good lower joint. Upper joint not brazed. Bronze not wet.
40 ^(c)	" " "	"	C ^(b)	Partly brazed.
41	" " "	"	C	Good lower joint. Upper joint not brazed. Bronze not wet.
51 ^(d)	" " "	"	C ^(b)	Good lower joint.
60 ^(f)	" " "	"	D ^(e)	Lower joint not brazed. Bronze not wet.
76	T (Cu & Inconel)	"	A	Brazed.
78	T (bronze de-aluminized)	"	A	No brazing.
43	T	Easy Flo 45	A	Poor. Partial brazing
44	T	Cu-Ag eutectic + 0.5% Li.	A	Poor. Partial brazing

(a) In run #14 chlorine gas was mixed with the dry hydrogen. The chlorine was not purified and apparently contained considerable O₂ or H₂O since a visible film of Al₂O₃ formed.

- (b) Only the first part of this type C experiment is considered. That is, the observations apply only to the 10-minute heating of the lower joint where no flux was used.
- (c) Specimen showed discoloration at end of run presumably due to contamination in tube from use of fluxes in previous runs.
- (d) This experiment actually describes a group of seven type C experiments. (# 40, 51, 52, 53, 54, 57, and 58). Satisfactory brazing took place at the lower joint.
- (e) Only the first part of this type D experiment is considered. That is, the observations apply only to the lower joint.
- (f) This experiment actually describes a group of six type D experiments (# 60, 63, 64, 65, 79, and 80). In none did brazing of the lower joint result.

Table II describes a number of experiments in which various miscellaneous materials were investigated as fluxes. The table is divided into five subgroups. In the first group (halogens) the chlorine was pre-mixed with the flowing hydrogen, whereas the iodine was applied with the powdered filler metal. The proprietary fluxes in subgroup 2 are believed to be based on borates. The Alcoa fluxes in subgroup 5 are designed for brazing aluminum and are believed to be based on alkali metal chlorides, perhaps with a fluoride, and possibly containing halides of aluminum, strontium and zinc. The composition of Dow #220 flux is believed to be 55 KCl, 28 CaCl₂, 12.5 BaCl₂ and 25 CaF₂.

In run 42, a larger proportion of TiH₂ to filler metal powder was used compared to Runs 48 and 49.

Table III describes the experiments wherein fluxes based on alkali or alkaline earth halides were investigated in regard to their ability to promote brazing in spite of a pre-formed Al₂O₃ film on the bronze. The filler metal was Coast Metals 53 in every case.

Table III has been arranged in three subgroups. Subgroup 1 contains fluxes based on a mixture of 5 parts LiCl, 4 parts KCl and 1 part NaCl. In run 66 the LiCl has been omitted in order to observe the effect of its absence. Subgroup 2 lists the experiments based on BaCl₂. If it were desired to braze by dipping the heat exchanger in molten flux, a flux based on BaCl₂ would be preferable on account of the lower volatility of BaCl₂. Subgroup 3 shows two experiments with a flux of 5 NaCl,

TABLE II

BRAZING EXPERIMENTS IN DRY HYDROGEN WITH VARIOUS FLUXES

Run No.	Specimen Type	Braze Metal	Experiment Type	Flux	Remarks
<u>1. Halogens</u>					
14	tube & fin	CM52 & 53	B	Chlorine	Mixture of Cl_2 & H_2 gas. Fair joint. ² Poor penetration into crevice.
12	T	"	A	Iodine	No joining
<u>2. Borates</u>					
8	T	"	A	Potassium pentaborate	Good joint
9	T	"	A	Handy & Harmon B	" "
10	T	"	A	Eutectic 16 B	" "
13	T	CM53	A	Handy B-1	" "
19	T	"	A	Microbraz 10	" "
<u>3. Alkaline agents</u>					
21	tube & fin	"	B	Trisod-phosphate	No joining
15	T	"	A	NaOH	No joining
16	T	"	A	$NaOH + NaCl$	Poor. Some joining
25	T	"	A	$NaCr + NaCN$	No joining
<u>4. Single halides</u>					
20	tube & fin	"	C	NaCl	Upper joint not brazed. Bronze not wet.
7	T	CM52 & 53	A	CuCl	No joining
11	T	"	A	NH_4Cl	" "
17	T	CM53	A	Cryolite	" "
28	T	"	A	$ZnCl_2$	" "
39	T	"	A	$LiCl$	" "

Table II (continued)

<u>Run No.</u>	<u>Specimen Type</u>	<u>Braze Metal</u>	<u>Experiment Type</u>	<u>Flux</u>	<u>Remarks</u>
<u>5. Mixed halides</u>					
24	T	CM53	A	MgCl ₂ + KCl	No joining
23	T	"	A	Dow flux # 220	" "
26	T	"	A	Alcoa flux # 34	Good joint
30	T	"	A	Alcoa flux # 53	Good joint
<u>6. Hydrides</u>					
42	T	"	A	TiH ₂	No joining
43	T	"	A	TiH ₂	Poor. Some joining
49	tube & fin	"	C	TiH ₂ (on upper & lower)	Lower joint brazed Upper joint not brazed
50	"	"	B	CaH ₂	Bronze fused
52	"	"	C	CaH ₂ (on upper & lower)	Lower joint partly brazed. Upper joint not brazed
51	"	"	C	ZrH ₂	Upper joint not brazed
53	"	"	C	5 LiCl 4 KCl 1 NaCl 1 TiH ₂	Upper joint brazed 4/5 around.

1 LiCl, 1 CuCl. This mixture is developed from those of subgroup 1 ; the KCl has been eliminated and the proportion of LiCl decreased, again for reasons of volatility.

These experiments in flux formulations were exploratory in nature and hence it was not considered expedient to know the relative proportions exactly. The indicated proportions are in the nature of guesstimates. Furthermore, many of the compounds used are deliquescent and were not pre-dried. Although precautions were taken to limit the amount of moisture picked up before the specimens could be sealed into the dry hydrogen atmosphere, this can be expected to have been only partially successful. In certain cases runs were made in which one of the flux ingredients was in the form of hydrated crystal. Very probably, superior results would result with lower moisture contents. In any future experiments to refine these flux compositions, the specimens might better be prepared in a dry box.

Heating-in-air experiments

To determine whether useful information regarding the effectiveness of fluxes could be obtained by an easier and quicker method, a simple torch-brazing experiment was carried out. An aluminum bronze panel was supported horizontally, a CM53 ring set on it, and covered with dry flux. The panel was heated from below with an oxy-gas torch until the filler metal melted. Table IV describes the experiments performed.

RESULTS

The degree of success achieved in the brazing tests has been indicated in the last column of Tables I, II and III as judged

TABLE III

BRAZING EXPERIMENTS IN DRY HYDROGEN WITH HALIDE FLUXES

Run No.	Specimen Type	Experiment Type	Flux		Remarks
<u>1. Fluxes based on alkali metal chlorides</u>					
36	T	A	5 LiCl 4 KCl 1 NaCl		Fair. Brazed half of length.
56	T	A	5 LiCl 4 KCl 1 NaCl	2 AlF ₃	No joining
55 (& 67)	T	A	5 LiCl 4 KCl 1 NaCl	2 SrCl ₂ .6H ₂ O	No joining
58	tube & fin	C	5 LiCl 4 KCl 1 NaCl	1 TiH ₂	Lower joint brazed Upper joint brazed 4/5 around.
62	T	A	5 LiCl 4 KCl 1 NaCl	2 FeCl ₂ .4 H ₂ O	Fair. Brazed 3/5 of length
37	T	A	5 LiCl 4 KCl 1 NaCl	1 CrCl ₃	Fair. Brazed 1/3 of length
63	tube & fin	D	5 LiCl 4 KCl 1 NaCl	2 CrCl ₃	No joining
74	T	A	5 LiCl 4 KCl 1 NaCl	2 AgCl	Fair. Brazed full length Bronze attacked
79	tube & fin	D	5 LiCl 4 KCl 1 NaCl	1 AgCl	Fair. Brazed all around Bronze attacked
32	T	A	5 LiCl 4 KCl 1 NaCl	1 ZnCl ₂	Good
53	tube & fin	C	5 LiCl 4 KCl 1 NaCl	$\frac{1}{2}$ ZnCl ₂	Poor. Brazed 2/5 around
57	"	C	5 LiCl 4 KCl 1 NaCl	2 ZnCl ₂	Fair. Brazed 3/5 around

Table III (continued)

Run No.	Specimen Type	Experiment Type	Flux		Remarks
33	T	A	5 LiCl 4 KCl 1 NaCl	1 CdCl ₂	Good
72	T	A	5 LiCl 4 KCl 1 NaCl	2 CdCl ₂	"
54	tube & fin	C	5 LiCl 4 KCl 1 NaCl	2 CdCl ₂	"
60	"	D	5 LiCl 4 KCl 1 NaCl	2 CdCl ₂	"
66	T	A	4 KCl 1 NaCl	1 CdCl ₂	Fair. Brazed full length but joint weak. Bronze not well wet.
34	T	A	5 LiCl 4 KCl 1 NaCl	1 CuCl	Good
64	tube & fin	D	5 LiCl 4 KCl 1 NaCl	2 CuCl	Good
61	T	A	5 LiCl 4 KCl 1 NaCl	2 NiCl ₂	Good
65	tube & fin	D	5 LiCl 4 KCl 1 NaCl	2 NiCl ₂	Good

2. Fluxes based on alkaline earth halides - for lower volatility

31	T	A	3 BaCl ₂ 5 CaCl ₂ 2 NaCl	1 NaF	No joining
29	T	A	3 BaCl ₂ 5 CaCl ₂ 2 NaCl	1 ZnCl ₂	Poor. Brazed for 3/8"
27	T	A	3 BaCl ₂ 5 CaCl ₂ 2 NaCl	1 NaF 1 ZnCl ₂	Good

Table III (continued)

Run No.	Specimen Type	Experiment Type	Flux	Remarks
69	T	A	9 BaCl ₂ 1 NiCl ₂ 1 LiCl	No joining
70	"	"	9 BaCl ₂ 1 CdCl ₂ 1 LiCl 1 NaCl	Fair, Brazed 1/3 of length
71	"	"	5 BaCl ₂ 5 LiCl ₂ 2 CdCl ₂ 1 NaCl	No joining
73	"	"	3 BaCl ₂ 3 SrCl ₂ 5 LiCl 2 CdCl ₂ 2 NaCl	No joining
<u>3. Fluxes bases on Alkali halides - lower volatility.</u>				
75	"	"	5 NaCl 1 CuCl 2 LiCl	Good
80	tube & fin	D	5 NaCl 1 CuCl 2 LiCl	Good

TABLE IV

EXPERIMENTS ON HEATING ALUMINUM BRONZE AND CM53 WITH FLUX IN AIR

Test No.	Flux		Result	Corresponding Brazing Experiment in H ₂			Correlation
				No.	Type	Result	
a	Alcoa #53		Bronze wet. Good.	30	A	Good	Good
b	Alcoa #34		"	26	A	Good	Good
c	Handy B-1		"	18	A	Good	Good
d	5 LiCl 4 KCl 1 NaCl		No wetting. Filler metal coalesced to a non-adherent sphere.	36	A	Fair	Fair
e	5 LiCl 4 KCl 1 NaCl	1 CdCl ₂	Bronze wet. Good	33	A	Good	Good
				54	C	"	
				60	D	"	
f	5 LiCl 4 KCl 1 NaCl	2 SrCl ₂ .6 H ₂ O ²	Poor	55	A	Bad	Fair
g	5 LiCl 4 KCl 1 NaCl	2 NaF 2 SrCl ₂ .6H ₂ O	Bad. Coales- ced to sphere				
h	5 LiCl 4 KCl 1 NaCl	2 AlCl ₃	Bad				
i	9 BaCl ₂ 1 LiCl	1 NiCl ₂	Bad	69	A	Bad	Good
j	5 LiCl 4 KCl 1 NaCl	2 CrCl ₃	Bad	63	D	Bad	Good
k	5 LiCl 4 KCl 1 NaCl	2 CuCl	Fair. Some wetting	34	A	Good	Fair
				64	D		
l	8 BaCl ₂ 1 LiCl 1 NaCl	1 CdCl ₂	? Braze Cu colored	70	A	Fair	?

Table IV (continued)

Test No.	Flux	Result	Corresponding Brazing Experiment in H ₂			Correlation
			No.	Type	Result	
m	5 BaCl ₂ 2 CdCl ₂ 5 LiCl 1 NaCl	? Braze Cu Colored	71	A	Bad	? Fair
n	3 BaCl ₂ 3 SrCl ₂ 5 LiCl 2 CdCl ₂ 2 NaCl	? "	73	A	Bad	? Fair
o	5 LiCl 2 AgCl 4 KCl 1 NaCl	Poor "	74	A	Fair	Fair
p	5 NaCl 1 CuCl 2 LiCl	Poor "	75	A	Good	Poor
q	5 NaCl 1 CdCl ₂ 2 LiCl	Fair "				

visually and by peeling the T-joints apart. This information has been supplemented, especially with tube-and-fin specimens, by the examination of metallographic sections.

From Table I it is apparent that a joint of high quality can be obtained even in the absence of flux, with the tube-and-fin specimen when it is rapidly brought to temperature in dry hydrogen (Runs 13, 22, 41, 51). Figures 4 and 5 show the excellent penetration of the filler metal into the crevice of specimen 13 and of the lower joint of specimen 22. Similar test conditions with a T-specimen (Run 2) gave joining only at limited areas where the filler metal had been preplaced or where the molten filler metal happened to come to rest. Brazing did not occur, however, when the specimen was pre-heated for 10 minutes in the dry hydrogen atmosphere (upper joint of Run 22 and 41). The filler metal then did not wet the bronze but ran up to form a collar around the Inconel tube. This can be seen in Fig. 6 of specimen 41. Brazing also did not occur when the hydrogen atmosphere was contaminated by the dissociation of the oxide film on Inconel (lower joint of Run 60). Fig. 9a shows how the filler metal formed a collar around the Inconel tube above the lower joint.

The lack of brazing in the lower joint of Run 20 and the relatively poor result in Run 21 was attributable to contaminating vapors in the furnace tube from the fluxes used in previous runs.

When chlorine was mixed into the flowing hydrogen stream (Run 14) the joint formed was not as good as in dry hydrogen alone (Run 13). Fig. 7 indicates the absence of penetration of the filler metal into the crevice apparently as a result of oxide film formed

Figure 4 - Photomicrograph of
Joint Formed in Dry
Hydrogen without
Flux. Specimen 13.
Unetched. X33.

Figure 5 - Photomicrograph of
Joint Formed in Dry
Hydrogen without
Flux. Specimen 22.
Lower Joint. Unetched.
X33.

Figure 6 - Photograph of Tube & Fin Specimen Showing Good Joint (Lower) Formed in Dry Hydrogen without Flux with Rapid Heating and Bad Joint (Upper) when Pre-Heated. Specimen 41.

Figure 7 - Photomicrograph of Joint Formed in Mixture of Hydrogen and Chlorine Gas Showing Lack of Penetration into Crevice. Specimen 14. Unetched. X33.

on the bronze from impurities in the chlorine gas. A filmy, readily-separable oxide film was observed on the bronze at the end of the run along with de-aluminization of the bronze as evidenced by a coppery rather than brassy surface color of the bronze.

The joint formed in Run 76, in which a pure copper panel was substituted for aluminum bronze, was observed to peel very readily but the separation was in the copper rather than through the joint. The apparent weakness of the joint was due presumably to the low strength of the pure copper after being fully annealed in the brazing operation. The failure to braze in Run 78 indicates that the de-aluminization by pre-oxidation was insufficient (or perhaps that the tube was contaminated with flux from previous runs).

In Runs 43 and 44 using silver solders the same temperatures were used as with the nickel-base Coast Metals alloys. Such temperatures are very high for silver brazing so that the effect of the lithium addition cannot be interpreted. Experiments at lower temperatures were of little assistance.

In Table II the satisfactory results with borate fluxes was demonstrated again (Runs 18 and 19) as it had been in the previous report (Runs 8, 9, and 10).

Rather surprisingly, agents in which Al_2O_3 is known to be soluble, cryolite and NaOH, did not promote brazing (Runs 15 and 17)

Single halides (Subgroup 4), even of compounds which subsequently proved to be effective additions to flux mixtures (e.g. NaCl, CuCl, LiCl and $ZnCl_2$), were totally ineffective.

The Alcoa fluxes gave excellent results (Runs 26 and 30) in spite of the fact that they are designed for brazing aluminum

alloys, an operation which is carried out at a much lower temperature.

Neither TiH_2 nor ZrH_2 was able to overcome the oxide film produced by the 10-minute preheating treatment (upper joint of specimens 49 and 51) when used alone although TiH_2 in alkali halides was effective (Run 59). Brazing of the lower joints in the Type C experiments resulted when TiH_2 or CaH_2 was used in sufficiently small amounts but this appears to be brazing in spite of the presence of the hydride rather than because of it.

Table III lists the more significant experiments in the development of flux formulations for overcoming the intentionally-formed thicker Al_2O_3 films. From subgroup 1 it can be seen that the addition of $ZnCl_2$, $CdCl_2$, $CuCl$ or $NiCl_2$ to the alkali halide base (5 LiCl, 4KCl, 1 NaCl) led to satisfactory brazing. Addition of $FeCl_2$, $CrCl_3$, $AgCl$ and TiH_2 gave poorer results. Addition of AlF_3 or $SrCl_2$ was ineffective. Run 66 shows that without LiCl in the mixture the results were not as good. Fig. 8b shows how in Run 54 the mixture of alkali and cadmium chlorides led to better penetration even after the 10-minute preheat treatment (upper joint) than in the lower-joint experiment without flux where the Al_2O_3 film was of minimum thickness (Fig. 8a). Fig. 9 shows the effect of this same flux on the upper joint of the Type D experiment (Run 60). The surface of the braze metal was uneven and spiny. Fig. 9a shows how the braze metal had flowed out of the bottom of the crevice, 9b shows the structure of the filler metal inside the crevice, 9c that of the lowest spiny mass, and 9d that of a ring of filler metal left

Figure 8 - Photomicrograph of Joints in Type C Experiment.
Specimen 54. Unetched. X50.

- (a) Lower Joint - No Flux.
- (b) Upper Joint - Pre-Heat plus Halide Flux
(5 LiCl, 4 KCl, 1 NaCl, 2 CdCl₂).

as a hump on the bronze fin at the position where the CM53 ring had been pre-placed. Fig. 9e shows the general appearance of specimen 60.

Fig. 10 shows the results obtained with the upper joint of a Type D experiment (Run 65) using mixed alkali and nickel halides as a flux. (The specimen has been deformed during the cutting and grinding operations in mounting). Fig. 10a shows the good penetration into the crevice, 10b the structure of the filler metal inside the crevice, 10c the structure in the fillet, and 10d the structure in the hump of braze metal left on the bronze fin where the braze metal ring had been preplaced.

At the brazing temperature of 1375°F the fluxes of subgroup 1 in Table III were quite readily volatile. Since for applications such as dip brazing a less volatile flux is preferable, an attempt was made to modify the flux toward this end. Table V is a compilation of the melting point, boiling point and solubility at room temperature of a number of materials of interest as flux ingredients. It can be seen that fluxes based on alkaline-earth chlorides should be less volatile than those based on alkali-metal chlorides. Subgroup 2 of Table III describes experiments to investigate fluxes based on BaCl_2 . Poor results were obtained except in Run 27 where both NaF and ZnCl_2 were added to a base of BaCl_2 , CaCl_2 and NaCl .

In subgroup 3 of Table III is shown the result of using a flux of 5 NaCl , 2 LiCl and 1 CuCl . This flux formulation can be expected to have a lower volatility than the fluxes of subgroup 1 by reason of the absence of KCl and the greater proportion

Figure 9 - Joint Formed with Type D Experiment. Specimen 60. Flux: 5 LiCl, 4 KCl, 1 NaCl, 2 CdCl₂.

(a) Photomicrograph of Upper Joint. Unetched. X50.

(b) Detail of Microstructure in Crevice. Etched Electrolytically in H₂SO₄. X250.

Fig. 9c

Fig. 9d

Fig. 9e

- (c) Detail of Filler Metal Flowed out of Crevice. Etched Electrolytically in H_2SO_4 . X250.
- (d) Detail of Filler Metal Remaining on Bronze as a Hump. Etched Electrolytically in H_2SO_4 .
- (e) Photograph of Specimen 60 Showing Rough Surface of Upper Joint (and Lack of Brazing of Lower Joint)

a

b

**Figure 10 - Joint Formed with Type D Experiment. Specimen 65.
Flux: 5 LiCl, 4 KCl, 1 NaCl, 2 NiCl₂.**

**(a) Photomicrograph of Upper Joint. Unetched.
X50.**

**(b) Detail of Microstructure in Crevice. Etched
Electrolytically in H₂SO₄. X250.**

Fig. 10c - Detail of Filler Metal in Fillet. Etched Electrolytically in H_2SO_4 . X250.

Fig. 10d - Detail of Filler Metal Remaining on Bronze as a Hump. Etched Electrolytically in H_2SO_4 . X250.

of NaCl (cf. Table V). Good results were obtained in both A and D type experiments. A much smoother surface was obtained on the braze metal than when Cd or Ni chlorides were used. Fig. 11a shows the nature of the penetration in the upper joint of specimen 80. The crevice was well penetrated but not fully to the bottom. Fig. 11b shows the structural detail of the filler metal inside the crevice. Fig. 11c shows the smooth fillet obtained on the upper joint.

Table IV summarizes the experiments in which a filler metal ring was set on a bronze panel, covered with flux, and heated with a torch in air until the filler metal melted. The corresponding furnace brazing experiments are also included in the table and it is seen that some degree of correlation exists between the two sets of results. However, the results in tests l to q were difficult to assess since the solidified braze metal had an abnormal appearance including a copper-colored surface.

DISCUSSION

That aluminum bronze can be brazed to Inconel in a dry hydrogen atmosphere in spite of the unfavorable thermodynamics is apparent from the brazing experiments without fluxes. T-specimens showed joining at isolated spots but without flow and with the braze metal exhibiting a high contact angle on the bronze (more correctly, perhaps, on the Al_2O_3 film on the bronze); tube-and-fin specimens, where little flow is required, brazed satisfactorily, as Figs. 4 and 5 show. That is, when the panels are first well cleaned of their oxide films and a high-purity hydrogen atmosphere is used in which the specimen is brought to temperature in as short

TABLE V
PROPERTIES OF INGREDIENTS OF FLUXES

<u>Compound</u>	<u>Deliquescent</u>	<u>Melting Point (°C)</u>	<u>Boiling Point (°C)</u>	<u>Solubility (gm/100 gm)</u>
LiCl	yes	613	1353	45
NaCl		801	1413	36
KCl		776		35
MgCl ₂		708	1412	35
CaCl ₂	yes	772	> 1600	60
SrCl ₂		873		44
BaCl ₂		962	1560	31
ZnCl ₂	yes	262	732	432
CdCl ₂		568	960	140
CuCl		422	1366	0.008
AgCl		455	1550	0.001
NiCl ₂	yes		973	64
LiF		870	1676	0.27
NaF		990	1700	4.2
BaF ₂		1280	2137	0.17
ZnF ₂		872		Sl. sol.
NiF ₂				0.02
CuF		908		insol.

a

b

c

Figure 11 - Joint Formed with Type D Experiment. Specimen 80.
Flux: 5 NaCl, 2 LiCl, 1 CuCl.

- (a) Photomicrograph of Upper Joint. Unetched. X50.
- (b) Detail of Microstructure in Crevice. Etched Electrolytically in H_2SO_4 . X500.
- (c) Photograph of Specimen 80 Showing the Smooth Fillet of Upper Joint (and Lack of Brazing of Lower Joint).

a time as two minutes, the Al_2O_3 film on the bronze does not become thick enough to prevent joining, although the extent of flow is very limited.

Unfortunately, it is not possible to meet all these prerequisites in the brazing of a heat exchanger: its relatively large mass results in a heating rate much slower than in the experiments with small specimens; its complexity makes it difficult to sweep out the contaminating oxygen which develops in the inner recesses of the unit from the dissociation of the oxide film on the Inconel tubes. To simulate these adverse conditions, so that methods of overcoming them might be investigated, the Type C and Type D experiments were designed. The equivalent of a slower heating rate was achieved by a ten-minute preheat at brazing temperature of the tube-and-fin specimen (upper joint in the Type C experiment) in the pure hydrogen atmosphere before applying the braze metal. (The lower joint serves as a control.) Under these conditions the Al_2O_3 film became thick enough to prevent the filler metal from contacting the bronze. It is interesting, in the light of the comparison between the thermodynamics of the oxidation of chromium and aluminum in the previous report, to observe that the Inconel is still very readily wet. As the thermodynamics predicts, the oxide film on the Inconel does dissociate in the pure hydrogen at brazing temperature and permits the braze metal to wet.

The equivalent of not sweeping the dissociation products away rapidly was achieved with the lower joint of the Type D experiment. Here again, even with a rapid heating rate, the bronze was not wet and the filler metal ran up onto the Inconel in the form of a collar. The dissociation of the Cr_2O_3 or $\text{NiO} \cdot \text{Cr}_2\text{O}_3$ film on the

Inconel foil and Inconel tube increased the partial pressure of oxygen within the Inconel wrapping. This thickened the Al_2O_3 film enough to prevent brazing. In the case of the upper joint in the Type D experiment, both a slow heating rate and ineffective sweeping of dissociation products were simulated.

One method of approaching the brazing problem in spite of the large mass and complexity of a heat exchanger would be to attempt to arrange the conditions in the actual brazing operation as similar to the laboratory tests as possible. There are a number of modifications which might contribute to this end:

1. Attempt to provide a hydrogen supply of a purity as close as possible to that in the laboratory tests.
2. Circulate the hydrogen at high velocity and direct it through the interstices of the heat exchanger with the aid of baffles.
3. Provide a gap or hole centrally in the heat exchanger into which the hydrogen flow would be directed by means of a perforated delivery tube.
4. Decrease the time to reach brazing temperature by rapid circulation of the hydrogen and by passing a high-temperature liquid such as NaK through the Inconel tubes. Auxiliary heating by passing current through the tubes or heating by induction would be difficult to control. The problem would still remain, however, of the high partial pressure of oxygen in the local atmosphere from the dissociation of the oxide film on the Inconel.

An alternative scheme would be to use a filler metal composition that would braze in spite of the presence of the thicker

Al_2O_3 film. It is possible that addition of lithium to the nickel-base brazing alloys would have this effect since the self-fluxing action of lithium-bearing braze metal has been demonstrated with silver solders. The experiments with lithium-bearing braze metal shown in Table I were inconclusive since the proper braze metal was not available. If an alloy such as CM53 can be obtained containing 0.5 to 1.0% lithium, it should be tested in a Type D experiment.

Still a third procedure would be to modify the surface of the aluminum bronze so that an Al_2O_3 film would not form. This was the purpose of experiments 76 and 78. First it was demonstrated that copper without aluminum was brazeable with good flow. Then a low-aluminum surface layer was prepared by pre-oxidizing the aluminum bronze and pickling off the oxide. In this case, however, brazing was unsuccessful. A preferable method of obtaining an aluminum-free surface layer would be to plate a thin layer of copper on the bronze. (This practice is followed successfully in silver brazing beryllium copper.) In service the aluminum would soon diffuse into the copper layer and provide the desired protection against scaling. Judging from experience at ORNL with similar plating experiments, it appears that the brazing temperature necessarily used with nickel-base filler metal is so close to the melting point of the aluminum bronze that the aluminum might diffuse into the copper layer during the period of heating for brazing and thus little would be gained.

A fourth possibility is to break up or disturb the Al_2O_3 layer on the bronze by ultrasonic vibrations. Superposition of this

method on the first and second schemes above would improve their feasibility. No experiments with ultrasonic vibrations were carried out since the generating equipment has not yet been obtained. Whether a large heat exchanger is amenable to such treatment has yet to be determined.

Should successful brazing of the heat exchanger not result from any of the foregoing schemes, brazing is still possible through the use of a suitable flux. Reluctance to use of a flux stems from the anticipated difficulty of removing every trace of flux before putting the unit in service and the resulting danger of a failure due to corrosion. The intricate nature of the assembly precludes any possibility of direct attack on the solidified flux so that its removal could be effected only by jets of water and steam. (Consideration might be given here again to assistance from ultrasonic vibrations.)

The results in Subgroup 2 of Table II show that fluxes based on borates give satisfactory joints. Unfortunately, such flux residues are not readily soluble so that considerable difficulty is to be expected in removing them.

A hydride flux is attractive on the basis that after decomposition the residue would be a metal and not necessarily contribute to corrosion. However, poor results were obtained except when the hydride was mixed with alkali chlorides (Table II, subgroup 6).

From the experimental results described in subgroups 3, 4 and 5 of Table II it was indicated that a suitable flux should be based on soluble halides with certain additives as "activators".

The design was to provide a soluble matrix and to maintain the proportion of insoluble products to a minimum. Thus when the matrix was dissolved away, the small amount of insoluble phase could be expected to wash out freely. Fluoride was to be avoided if possible due to the low solubility of fluorides relative to the other halides, and also due to the corrosive nature of fluorides in the event that complete removal was not achieved.

From subgroup 1 of Table III it can be seen that satisfactory fluxes result when chlorides of zinc, cadmium, copper or nickel are added to a base of mixed alkali-metal chlorides including lithium. The CuCl addition is preferred because a smoother braze is obtained and because its use does not introduce a foreign metal. If cadmium or zinc chloride were used, any of the cadmium or zinc which became part of the joint might interfere with the development of the proper barrier-like characteristics of the Al_2O_3 or Cr_2O_3 films on which the high-temperature resistance depends. The low solubility of CuCl may be a disadvantage.

Modification of the flux composition toward lower volatility was attempted in the event that dip brazing should be followed. Formulations based on the less volatile $BaCl_2$ gave poor results except when fluoride additions also were made. Since fluorides were suspect from corrosion considerations, the original formulation was adhered to but was modified in the direction of lower volatility. The KCl was eliminated and the proportion of NaCl increased and LiCl decreased. These changes are consistent with the boiling-point data shown in Table V. The preferred composition thus became the mixture of 5 parts NaCl, 2 parts LiCl and 1 part CuCl, the satisfactory results of which are shown in subgroup 3 of Table III and in Fig. 11.

Although it is to be expected that minor amounts of insoluble compounds in the flux residue will be washed out when the soluble matrix is dissolved away, it remains to be determined by corrosion tests whether small amounts of chloride or fluoride left as a film on the bronze and Inconel would interfere with their high-temperature corrosion resistance. Fluoride might turn out to be unobjectionable if a negligible amount is retained or if it is volatilized in service. Similarly, additions of CdCl_2 and ZnCl_2 might be found not to interfere with the formation of barrier films on the metal surfaces. Corrosion tests in the presence of flux could determine how deleterious is the effect of incomplete flux removal.

Other avenues still to be investigated are the effect of a lithium addition to the braze metal for brazing without flux, the effect of ultrasonic vibrations in promoting brazing, and improvement of the flux formulation by further experiments including the use of moisture-free fluxes.

From the results of the experiments with fluxes it is possible to advance a reasonably consistent explanation of the function of the various flux ingredients on the basis of thermodynamic considerations.

In order for the balance of interfacial tensions to be satisfactory for spreading of the braze metal, an oxide-free surface appears to be necessary. It has been established above that an Al_2O_3 film forms on aluminum bronze even in dry hydrogen and at brazing temperature, and further that this film, if thicker than a minimum, prevents wetting of the bronze by the braze metal. The function of the flux is to present to the liquid filler metal

a surface on which spreading can take place. Mere solution of the Al_2O_3 film may not be sufficient. After the initial Al_2O_3 film dissolves, if more Al_2O_3 continually reforms, spreading need not occur. The Al_2O_3 can form from the reaction of aluminum diffusing to the bronze surface with oxygen in the flux. A further function of the flux, then, is to modify the system so that Al_2O_3 does not continue to form.

LiCl has been shown to be an effective additive. Lithium oxide has a high negative free energy of formation relative to Na_2O or K_2O and hence can be expected to decrease the activity or effective concentration of oxygen in the flux. (The free energies of formation of a number of oxides of interest have been included for convenience as Table VI). It is not necessary that the Li_2O be insoluble in the fused salt since the oxygen activity will be lowered by reason of much of the oxygen existing as a molecular solution of Li_2O . A second contribution of the lithium ion would be to promote the solution of the Al_2O_3 by the formation of a mixed oxide. Lithium is known to form low-melting slags with most of the metallic oxides.

Since the experiments demonstrate that the presence of a metal salt, such as CuCl or NiCl_2 , is necessary in addition to the LiCl , it follows that the lithium effect is not sufficient. If the equation for the oxidation of aluminum is written as

the equilibrium constant in terms of activities is

$$K = \frac{a_{\text{Al}_2\text{O}_3}}{a_{\text{Al}}^2 a_{\text{O}}^3}$$

TABLE VI
FREE ENERGY OF FORMATION OF OXIDES

<u>Oxide</u>	<u>AF°</u>	<u>Oxide</u>	<u>AF°</u>
Li ₂ O	-99.3	ZnO	-43.5
Na ₂ O	-51.6	Al ₂ O ₃	-300.9
K ₂ O	-29.8	CdO	-24.4
CaO	-118.4	Cu ₂ O	-18.7
SrO	-111.2	B ₂ O ₃	-229.7
BaO	-103.5	Cr ₂ O ₃	-190.8
Ag ₂ O	+ 7.7	H ₂ O	-42.0
TiO	-94.4	FeO	-43.2
ZrO ₂	-202.7	NiO	-20.6

It is more instructive to write the deoxidation constant,

$$K_{\text{deox.}} = \frac{a_{\text{Al}}^2}{a_{\text{O}}^3}$$

If the product $a_{\text{Al}}^2 \cdot a_{\text{O}}^3$ is maintained below the value of $K_{\text{deox.}}$, Al_2O_3 will not form. LiCl in the flux decreases the activity of oxygen but brazing does not occur, indicating that the deoxidation constant is still exceeded. A reasonable assumption as to the function of, say, NiCl_2 in the flux is to decrease the activity of the aluminum in the bronze. This it does by reason of the lower solution potential of nickel relative to aluminum. The pertinent reaction is described by the equation.

Thus, nickel displaces aluminum on the lattice sites at the surface of the bronze and the activity of aluminum in the copper is thereby reduced. Now the product $a_{\text{Al}}^2 \cdot a_{\text{O}}^3$ is below the deoxidation constant so that Al_2O_3 is not possible thermodynamically. The smaller negative free energy of formation of NiO (and also Cu_2O , ZnO , CdO , FeO , Ag_2O and even Cr_2O_3) relative to Al_2O_3 precludes the possibility of a film of NiO forming under these experimental conditions. The two properties required, then, of the metal whose chloride is to be used as an additive, are a lower solution potential than aluminum, and a less negative free energy of formation for its oxide than for Al_2O_3 . Still another function of the NiCl_2 could be to decrease the activity of oxygen in the flux, as did the LiCl , by forming the spinel type of mixed oxide, $\text{NiO} \cdot \text{Cr}_2\text{O}_3$.

CONCLUSIONS

1. Aluminum bronze can be brazed to Inconel with nickel-base filler metal provided that a high purity hydrogen atmosphere is used and that the work is raised rapidly to brazing temperature. Three minutes to reach brazing temperature is satisfactory but 10 minutes is too long. Only limited flow is obtained so that the filler metal must be pre-placed where the joint is to be made.
2. Laboratory experiments using tube-and-fin specimens successfully simulate the conditions which exist in brazing a massive heat exchanger. These conditions are a slow heating rate and local contamination of the hydrogen atmosphere from the dissociation of the oxide film on the Inconel tubes.
3. Fluxes based on borates are effective in promoting brazing. Such fluxes, however, are undesirable due to their low solubility. They would thus be difficult or impossible to remove from an intricate heat exchanger, leading to possible corrosion failure in service.
4. Fluxes based on mixed halides successfully promote brazing. These are more readily soluble and thus should not contribute a corrosion hazard. A preferred mixture is 5 NaCl, 2 LiCl and 1 CuCl.
5. The mechanism of fluxing with halide fluxes appears to be based on the presence of lithium ion in an alkali-metal halide with the further addition of the halide of zinc, cadmium, nickel or copper. This results in a decrease in the activity

of oxygen in the flux and of aluminum in the bronze such that the product $a_{Al}^2 \cdot a_O^3$ does not exceed the deoxidation constant.

APPENDIX

TABLE VII

COMPLETE COMPILATION OF BRAZING EXPERIMENTS

Run No.	Temp. (°F)	Braze Metal	Specimen Type	Experiment Type	Plastic Binder	Flux	Result
1	1855	CM52	T	A	Microbraz	None	Poor. Brazing at limited areas.
2	1835	"	"	"	"	"	Poor. Brazing at limited areas.
3	1916	"	"	"	"	"	Poor. Brazing at limited areas.
4	1875	"	"	"	Parlon	"	Bad.
5	1890	"	"	"	Geon	"	"
6	"	"	"	"	Parlon	"	"
7	1870	CM52 3 53	"	"	Microbraz	CuCl	"
8	1890	"	"	"	"	Pot. penta-borate	Good
9	"	"	"	"	none	Handy & Harmon "H"	Good
10	"	"	"	"	"	Eutectic 16-B	"
11	"	"	"	"	Microbraz	NH ₄ Cl	Bad
12	"	"	"	"	"	Iodine	"
13	1870	"	tube & fin	B	none	none	Good. Flowed into crevice
14	"	"	"	B	"	Chlorine	Fair. Poor Penetration
15	1865	CM53	T	A	"	NaOH	Bad.
16	"	"	"	"	"	NaOH NaCl	Poor. Some joining
17	1870	"	"	"	"	Cryolite	Bad.

TABLE VII (continued)

Run No.	Temp. (°F)	Braze Metal	Specimen Type	Experiment Type	Plastic Binder	Flux	Result
18	1070	CM53	T	A	none	Handy B-1	Good.
19	1065	"	"	"	"	Microbraz 10 paste-	Good.
20	1035	"	tube & fin	C	"	NaCl	Lower joint not brazed, Upper joint not brazed
21	"	"	"	"	"	Trisod. phosphate	Lower joint partly brazed, Upper joint not brazed.
22	"	"	"	"	"	None	Lower joint brazed. Upper joint not brazed
23	"	"	T	A	"	Dow flux # 220	Bad
24	"	"	"	"	"	MgCl ₂	"
25	"	"	"	"	"	KCl	"
26	"	"	"	"	"	NaCN	"
27	"	"	"	"	"	NaCl	"
28	"	"	"	"	"	Alcoa flux #34	Good
29	"	"	"	"	"	3 BaCl ₂ 1 NaF 5 CaCl ₂ 1 ZnCl ₂ 2 NaCl	"
30	"	"	"	"	"	ZnCl ₂	Bad
31	"	"	"	"	"	3 BaCl ₂ 1 ZnCl ₂ 5 CaCl ₂ 2 NaCl	Poor. Brazed for 3/8"
32	1075	"	"	"	"	Alcoa flux #53	Good
33	"	"	"	"	"	3 BaCl ₂ 1 NaF 5 CaCl ₂ 2 NaCl	Bad
34	"	"	"	"	"	5 LiCl 1 ZnCl ₂ 4 KCl 1 NaCl	Good

TABLE VII (continued)

Run No.	Temp. (°F)	Braze Metal	Specimen Type	Experiment Type	Plastic Binder	Flux	Result
33	1875	CM53	T	A	none	5 LiCl 1 CdCl ₂ 4 KCl 1 NaCl	Good
34	"	"	"	"	"	5 LiCl 1 CuCl 4 KCl 1 NaCl	"
35	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl	Lost run, Gas exit plugged.
36	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl	Fair. Brazed half length
37	"	"	"	"	"	5 LiCl 1 CrCl ₃ 4 KCl 1 NaCl	Fair. Brazed 1/3 of length
38	"	"	"	"	"	LiCl	Lost run. Gas exit plugged.
39	"	"	"	"	"	LiCl	Bad
40	"	"	tube & fin	C	"	5 LiCl 1 CdCl ₂ 4 KCl 1 NaCl	Lower joint partly brazed Upper joint partly brazed

Cleaned accumulated salts from furnace tube.

41	"	"	"	"	"	none	Lower brazed. Upper not brazed.
42	"	"	T	A	Microbraz	TiH ₂	Bad
43	"	Easy Flo 45	"	"	none	none	Poor. Partial brazing at bottom
44	"	Cu-Ag eutectic +0.5Li.	"	"	"	"	Poor.

TABLE VII (continued)

Run No.	Temp. (°F)	Braze Metal	Specimen Type	Experiment Type	Plastic Binder	Flux	Result
45	1350	Easy Flo 45	T	A	none	none	Bad
46	"	Cu-Ag eut.+ 0.5 Li.	"	"	"	"	No melting. Temp. too low
47	1400	"	"	"	"	"	Bad
48	1375	CM53	"	"	Microbraz	"	Poor. Some brazing
49	"	"	tube & fin	C (modified)	none	TiH ₂ on both upper & lower joint	Lower joint brazed, Upper joint not brazed.
50	"	"	"	B	"	CuH ₂	Bronze melted
51	"	"	"	C	"	ZrH ₂	Lower joint brazed. Upper joint not brazed.
52	"	"	"	"	"	CuH ₂	"
53	"	"	"	"	"	5 LiCl 1/2 ZnCl ₂ 4 KCl 1 NaCl	Lower joint brazed. Upper joint not brazed. 3/5 around
54	"	"	"	"	"	5 LiCl 2 CdCl ₂ 4 KCl 1 NaCl	Lower joint brazed. Upper joint brazed.
55	"	"	T	A	"	5 LiCl 2 CdCl ₂ 4 KCl .6H ₂ O 1 NaCl	Bad
56	"	"	"	"	"	5 LiCl 2 AlF ₃ 4 KCl 1 NaCl	"
57	"	"	tube & fin	C	"	5 LiCl 2 ZnCl ₂ 4 KCl 1 NaCl	Lower joint brazed. Upper joint not brazed. 3/5 around
58	"	"	"	"	"	5 LiCl 1 TiH ₂ 4 KCl 1 NaCl	Lower joint brazed. Upper joint not brazed. 4/5 around.

TABLE VII (continued)

Run No.	Temp. (°F)	Braze Metal	Specimen Type	Experiment Type	Plastic Binder	Flux	Result
59	1875	CM53	tube & fin	D (modified)	none	none	Neglected to evacuate air. No brazing.
60	"	"	"	D	"	5 LiCl 4 KCl 1 NaCl 2 CdCl ₂	Lower joint not brazed. Upper brazed.
61	"	"	T	A	none	5 LiCl 4 KCl 1 NaCl 2 NiCl ₂	Good
62	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl 2 FeCl ₂ .4H ₂ O	Fair. Brazed 3/5 of length
63	"	"	tube & fin	D	"	5 LiCl 4 KCl 1 NaCl 2 CrCl ₃	Lower joint not brazed. Upper joint not brazed.
64	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl 2 CuCl	Lower joint not brazed Upper joint brazed.
65	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl 2 NiCl ₂	"
66	"	"	T	A	"	4 KCl 1 NaCl 1 CdCl ₂	Fair. Brazed full length. Weak joint. Poor wetting
67	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl 4 SrCl ₂ .6H ₂ O	Bad.
68	"	"	"	De-aluminized bronze	Micro-braz	none	Bad.
69	"	"	"	A	none	9 BaCl ₂ 1 LiCl 1 NiCl ₂	"

TABLE VII (continued)

Run No.	Temp. (°F)	Braze Metal	Specimen Type	Experiment Type	Plastic Binder	Flux	Result
70	1075	CM53	T	A	none	8 BaCl ₂ 1 LiCl 1 NaCl	1 GdCl ₂ 3 Fair. Brazed 1/3 of length
71	"	"	"	"	"	5 BaCl ₂ 5 LiCl 1 NaCl	2 CdCl ₂ Bad
72	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl	2 CdCl ₂ Good
73	"	"	"	"	"	3 BaCl ₂ 5 LiCl 2 NaCl	3 SrCl ₂ 2 CdCl ₂ Bad
74	"	"	"	"	"	5 LiCl 4 KCl 1 NaCl	2 AgCl Fair. Brazed full length
75	"	"	"	"	"	5 NaCl 2 LiCl	1 CuCl Good.
76	"	"	"	Copper Penel	Micro-braz	none	Fair. Brazed 3/5 of length
77	"	"	"	De-aluminized bronze	"	"	Lost run.
78	"	"	"	"	"	"	Bad.
79	"	"	tube & fin	D	none	5 LiCl 4 KCl 1 NaCl	1 AgCl Lower joint not brazed. Upper joint fair
80	"	"	"	"	"	5 NaCl 2 LiCl	1 CuCl Lower joint not brazed. Upper joint brazed.

PUBLICATION FORM (CONTINUED)

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