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Special Summary Report on M551, M552, and M553(Adhesion-Cohesion Phenomena)

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16. ABSTRACT

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a) Brazing and welding of metal structures in an orbital near zero gravity condition are quite feasible.

b) Design of joints for fabrication in zero gravity will place less emphasis on the tolerances and proximity of the adjacent structures than on the quantity of liquid metal available.

c) Brazing of metallic joints has many advantages over electron beam welding for practical reasons: simplicity, launch weight, development costs, joint design tolerances, remotization, etc.

d) No evidence of different physical or mechanical properties of liquid metals in zero gravity was observed. However, many differences in liquid behavior were observed. Many of these effects have been called adhesion-cohesion phenomena.

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FOREWORD

This special summary report narrates some analyses and conclusions of the team of technical people involved in the Skylab Experiments M551, 552 and 553. The object is to provide the most significant observations pertaining to adhesion-cohesion (surface energy) related phenomena in these three experiments in one document. Each specialist has previously written his own detailed and specific report in his functional area of expertise. This report comprehensively summarizes observations of adhesion-cohesion phenomena as reported by the specialists identified in Table 1. It has been agreed upon that the opinions of these specialists with regard to adhesion-cohesion phenomena will be reported here as an approximate consensus, and not specifically credited to any one person of this list. Through reports and many meetings, all of the persons in Table I have contributed to the analysis of the adhesion-cohesion phenomena in zero gravity.

A supplementary report for analysis of continuing efforts in Experiment M551 will be written later.

The NASA Contracting Officer's Representative for this study is Mr. James R. Williams, S&E-PT-M. The NASA Principal Investigators for the three experiments involved in this report are Messrs. R. M. Poorman (M551), S&E-ASTN-MM; J. R. Williams (M552), S&E-PT-M; and, E. A. Hasemeyer (M553), S&E-PT-MWM. All three men are of the Process and Engineering group at Marshall Space Flight Center (MSFC).

TABLE I. FIVE SCIENTIFIC DISCIPLINE TEAMS
(Asterisks for the 4 Special Summary Report Authors)

Team Function	Experiment Number	Contributing Investigators	Organization
I. Adhesion-Cohesion Phenomena	M551, 552, 553	J. M. Tobin*	Westinghouse Astronuclear Lab
		R. Kossowsky	Westinghouse Research Lab
		S. V. Bourgeois	Lockheed Missile & Space (Huntsville)
		W. A. Zisman	Office of Naval Research
	M551, 552	C. M. Adams	University of Wisconsin
	M551, 553	M. R. Brashears	Lockheed Missile & Space(Huntsville)
II. Convection & Solidification Analysis	M551, 552, 553	S. V. Bourgeois*	Lockheed Missile & Space(Huntsville)
		P. Grodzka	Lockheed Missile & Space(Huntsville)
	M551, 552	C. M. Adams	University of Wisconsin
	M553	C. H. Li	Grumman Aerospace Corp.
		D. J. Larson	Grumman Aerospace Corp.
		T. Z. Kattamis	University of Connecticut
		A. E. Wechsler	Arthur D. Little, Inc.
		E. T. Peters	Arthur D. Little, Inc.
III. Specimen Evaluation (metallography, etc.)	M551, 552	R. E. Monroe*	Battelle Memorial Inst. -Columbus
		H. E. Pattee	Battelle Memorial Inst. -Columbus
		C. M. Adams	University of Wisconsin
		R. W. Heine	University of Wisconsin
		T. A. Siewert	University of Wisconsin
	M553	J. L. Brown	Georgia Institute of Technology
		J. L. Hubbard	Georgia Institute of Technology
		J. W. Johnson	Georgia Institute of Technology
		C. H. Li	Grumman Aerospace Corporation
		D. J. Larson	Grumman Aerospace Corporation
		P. C. Johnson	Arthur D. Little, Inc.
		E. T. Peters	Arthur D. Little, Inc.
		A. E. Wechsler	Arthur D. Little, Inc.
		T. Z. Kattamis	University of Connecticut
IV. Isotope Tracer Studies	M552	E. H. Kobisk	Oak Ridge National Laboratory
		D. N. Braski	Oak Ridge National Laboratory
		H. L. Adair	Oak Ridge National Laboratory

Team Function	Experiment Number	Contributing Investigators	Organization
V. Thermal Analysis	M551, 552	K. Masubuchi*	Massachusetts Inst. of Technology
		T. Muraki	Massachusetts Inst. of Technology
	M551, 553	M. R. Brashears	Lockheed Missile & Space(Huntsville)
		S. J. Robertson	Lockheed Missile & Space(Huntsville)
	M553	A. E. Wechsler	Arthur D. Little, Inc.

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I. INTRODUCTION

Under Contract NAS 8-28730, Westinghouse was experimentally measuring and analyzing some adhesion-cohesion properties of the liquid metals used in Skylab MS/MS Experiments M551 (Metals Melting), M552 (Exothermic Brazing), and M553 (Sphere Forming). This effort was part of a team effort of similarly contracted technical investigators being coordinated by the Contracts Officer Representatives and the Principal Investigators at MSFC for these three experiments. The other contractors report separately.

Contract NAS 8-28730 has a starting date of May 15, 1972, and a completion date of December 15, 1973. The program was executed in four parts, three work phases and a special summary report:

Phase A.	Preparation of a ground base study plan (1st to 3rd month).
Phase B.	Laboratory test program (3rd to 18th month).
Phase C.	Experiment analysis program (14th to 19th month).
Special Summary Report.	Analysis of adhesion-cohesion phenomena (19th month).

Reporting of progress included Monthly reports, Phase A Summary Report, Phase B Summary Report, Final Report (all three Phases), plus a Special Summary Report for all adhesion-cohesion phenomena observed by all investigators.

Phase A. The objective for Phase A was to define a laboratory test program for Phase B, which was coordinated with, and complemented the efforts of the other investigators. As a result of Phase A, the contracted investigators were given different roles. Several were assigned to characterize and evaluate both ground (Phase B) and Skylab flight (Phase C) specimens. Others were to perform thermal analysis and convection analysis.

Although the analytical equations and models were available to mechanically analyze the convection, wetting, liquid flow, and adhesion phenomena; it was found that basic surface properties data were generally not available. This contract effort was assigned to obtain these data both experimentally and analytically in support of the convection analysis effort for M551, 552, and 553. The required data for specific liquid metals were contact angles, spreading temperatures, work of adhesion, surface energy, and both the composition and temperature variation of surface energies. These requirements were defined for Phase B of this contract.

Phase B. Contract NAS 8-28730 was changed to limit the scope to Experiments 551, 552 and 553. The laboratory test program defined in Phase A was conducted in Phase B. The results were transmitted to all investigators for use in their analyses

Phase C. Data from ground base tests, KC-135 jet parabolic flight tests and the Skylab flight have been provided to this investigator by MSFC for the purpose of experiment analysis. By comparison of ground and flight specimen evaluation it was expected to determine the effect of zero gravity on adhesion-cohesion phenomena. Significant aspects of this analysis developed by all investigators are reported here. All adhesion-cohesion phenomena observed have been evaluated for inclusion in this Special Summary Report.

The importance of adhesion-cohesion phenomena to the utilization of orbital zero gravity (mass acceleration) conditions is recognized by the Process and Engineering Laboratory at MSFC and the contracted scientific advisors for the Materials Science/Manufacturing in Space (MS/MS) program on Skylab.

Greater understanding and more meaningful analysis of the mechanics of fluid motion in these experiments require measurement of liquid metal surface energies and both the temperature and the concentration coefficients of variation of surface energies for the liquid metals used. These measurements were performed on this contract.

However, none of these three MS/MS experiments were specifically designed to obtain quantitative information on adhesion-cohesion phenomena. Many qualitative observations can be made by means of a comparison of evaluations and characterizations from ground base (one G), parabolic jet flight (zero G) and Skylab flight (zero G) test results on these three experiments. Since these observations are usually independently made by several of the principal investigators, specific credit is not given. The list of the principal investigators and some of their associates was given in Table I in the FOREWORD to this report.

2. CONCLUSIONS

The conclusions of the team of specialists can be generalized into a few statements which are given below:

a) Brazing and welding of metal structures in an orbital near zero gravity condition are quite feasible.

b) Design of joints for fabrication in zero gravity will place less emphasis on the tolerances and proximity of the adjacent structures than on the quantity of liquid metal available.

c) Brazing of metallic joints has many advantages over electron beam welding for practical reasons: simplicity, launch weight, development costs, joint design tolerances, remotization, etc.

d) No evidence of different physical or mechanical properties of liquid metals in zero gravity was observed. However, many differences in liquid behavior were observed. Many of these effects have been called adhesion-cohesion phenomena.

3. ADHESION-COHESION PHENOMENA

It was anticipated and later indicated by observations that the absence of most of the gravity forces which affect the behavior of liquids on earth does not change the basic properties of adhesion of liquid metals to solids or cohesion of the liquid to its self.

When not opposed by the force of gravity, the surface energy driven forces caused remarkable effects in the flow, wetting, spreading, mixing, and morphology of solidified liquid metals.

It is likely that a practical use of orbital zero gravity conditions can be made using these effects.

The physically measurable surface properties of wetting angle, cohesion, surface energy, interfacial energy, vapor pressure, etc., are not expected to be changed by zero gravity. What is changed is the behavior of liquids when not opposed by the force of gravity. These effects are called the adhesion-cohesion phenomena in zero gravity, as discussed below.

Surface Reduction and Wetting Forces. A liquid drop surface behaves as if it attempts to reduce its surface area. However, if the liquid drop contacts a surface which it wets well, it tends to spread and greatly increase its surface area. The first phenomenon is due to liquid cohesion and results in surface reduction forces. The second phenomenon occurs when the tendency for adhesion and wetting of the liquid on another surface (solid or liquid) exceeds the tendency for cohesion. The resulting wetting forces cause spreading of the liquid on the other surface. If the contact angle approaches zero, complete spreading of the liquid on the entire surface of the other material occurs.

Capillary Flow and One G. All forces of adhesion and cohesion are expected to be the same at one G as at zero G. But the effects, or the phenomena produced by these surface energy activated forces can be pronounced in zero G because they are not opposed by the force of gravity.

An example is that of the flow of liquid into a capillary at one G. When a capillary is wetted by a liquid, and the liquid is in coherent contact with a larger body of liquid, some of the liquid will flow into the capillary until a balance of opposing forces occurs. The force of gravity is opposed against the attractive force of wetting of the liquid to the capillary walls. This is a well known example. But it is usually postulated that the capillary is vertically up, i.e., liquid flow by capillary attraction opposes gravity and a hydrostatic pressure gradient is developed in the column depending on the column height, liquid specific gravity, and a constant force of gravity. Also it is assumed that the volume of liquid available to fill the capillary to the height at which these forces are at balance is sufficient.

Flow and Shape of Isothermal Homogeneous Liquid Drops. On earth, the most significant natural force in determining the flow of liquid is gravity. The shape of a liquid at rest is determined by its container. The next most significant natural forces in determining flow and shape of liquids at one gravity result from the coherence of the liquid to itself and the adherence of the liquid to another solid or liquid. In zero gravity all the imposed mechanical forces, adhesion-cohesion phenomena, viscosity and internal damping predominate in determining the flow and shape of liquids.

A drop of liquid drifting in zero gravity will tend to become a sphere if it does not contact another surface. It will tend to cohere and not break into smaller drops unless it is extremely agitated. A rotational motion elongates the drop and if a sufficient centrifugal force occurs to overcome coherence the drop will break up into 2 or more smaller drops. Strong convective flow can cause the drop to break up. Eventually, all internal flow currents in the drops are stilled by the resistance of the liquid to flow and the mechanical energy is converted to heat. When this occurs the drifting drop becomes a nearly perfect sphere.

As a class of liquids, liquid metals have high surface energies and high coherence. Therefore they have relatively low tendencies to break into smaller drops and take long times to dampen the oscillating surface and shape motions. Further they have a strong tendency to adhere to other solid metal surfaces, which is applied in the process of welding and brazing.

If a low viscosity liquid completely wets its container, it can flow all over the solid surface, making inside and outside of the container the same for the liquid. Liquid can be located in zero G by attachment to a surface it partially wets. Liquid containment is possible in tubes and bottles. Use of liquid in space is possible by using the natural phenomena of adhesion and cohesion.

Surface Energy, Adhesion and Cohesion. Surface energy is a basic manifestation of the thermodynamic property of cohesive energy in the condensed states. Gases condense to liquids or solids when the cohesive bonding forces between their atoms or molecules exceeds the opposing tendency to vaporize. At sufficiently low temperatures even inert gas atoms like helium will condense to a coherent liquid as a result of the weak attraction of van der Waal's forces.

Interior atoms (or molecules) removed by more than 100 atoms distance from a free surface have a symmetrical attraction to the neighboring atoms when averaged over time. Surface atoms do not have symmetrical attraction, and the unsatisfied bonding normal to the surface results in a net attraction of surface atoms to the interior. This results in a surface tension, which is a net mechanical tension the surface layer tangential to the surface curvature. To evaluate the surface energy in the case of liquids, the mechanical effects of the surface tension are measured. The cohesion of a liquid increases directly with its surface energy. A degree of bonding of surface atoms to the adjacent phase across the interfacial surface will decrease the surface energy between phases and increase adhesion between the two phases. In the case of liquid/liquid and liquid/solid interfaces the work (energy) of adhesion can be appreciable.

Values of surface energies are available for only some of the elements of the periodic table. Measurements for metallic alloys and the temperature coefficients of variation for the elements and their alloys are scarce and unreliable. Most reliable measurements of surface energies are made with covalent bonded molecular liquids near room temperature. One elemental liquid metal, mercury, has been well characterized near room temperature. However, experimental difficulties plague the measurements of surface energies of other liquid metals at elevated temperatures.

4. GROUND BASE SURFACE ENERGY MEASUREMENTS

No zero G experiment was explicitly designed to yield quantitative surface energy data.

Nevertheless, all observations of contact angles, fillets, menisci, pores, bubbles, etc., were carefully gleaned to find if surface energy is the same in zero G conditions. No evidence to the contrary was found.

Measurements of surface energy and the temperature coefficient of variation of surface energy were made for most of the liquid metals in the M551, 552 and 553 experiments in carefully conducted ground base tests. Figures 1, 2 and 3 give the results in graphical form showing the surface energy as a function of temperature. All liquid metals tested showed a significantly decreasing surface energy (at the liquid/vapor interface) with increasing temperature. Thus, strong convection currents (due to the Marangoni effect) were analytically prediced to occur in electron beam (EB) heating of liquid metals as a result of the strong temperature gradients. These convection currents were observed by movie camera pictures and many other indirect evidences.

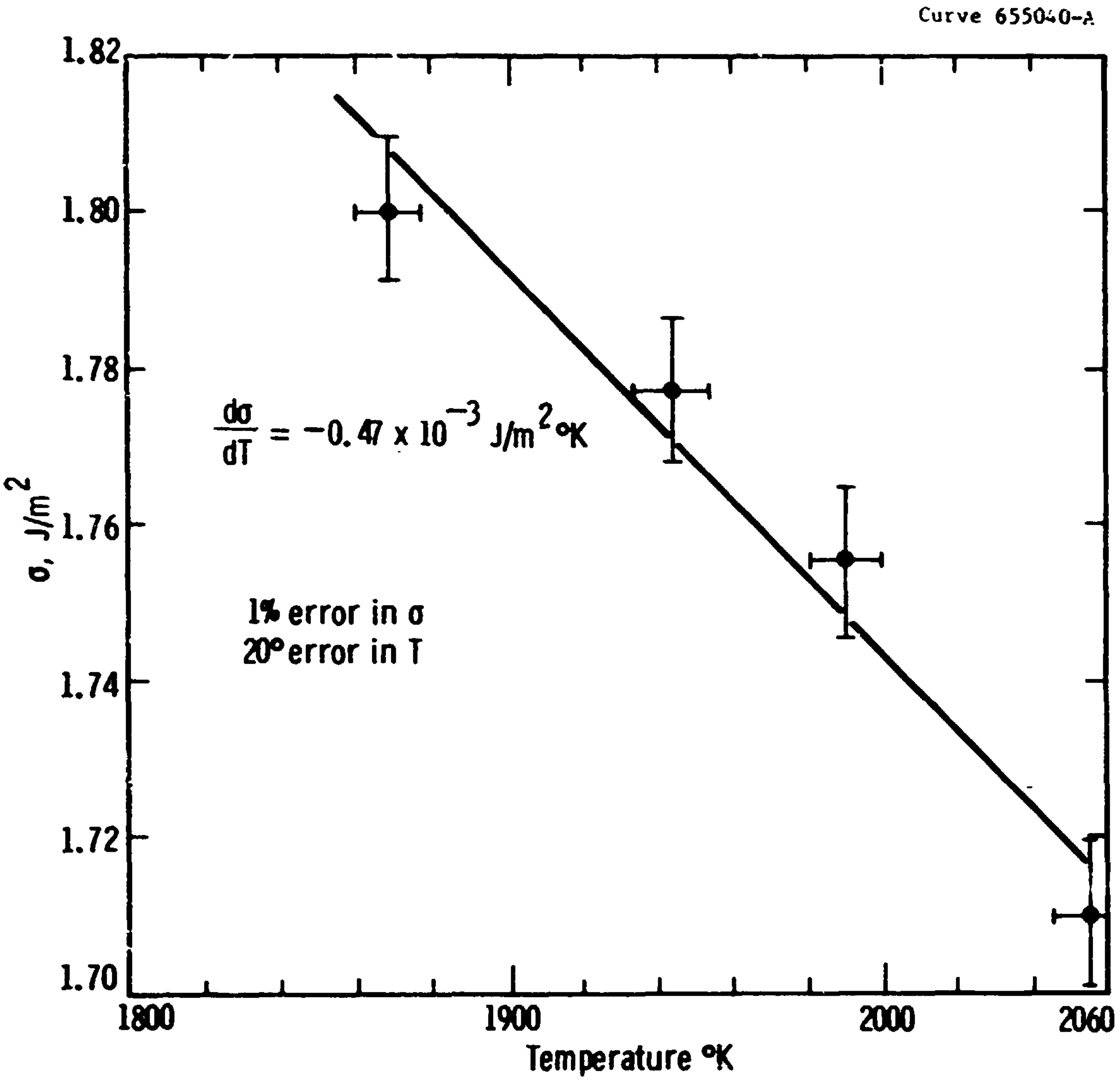

Figure 1. Surface energy versus temperature, SS 304L alloy. Al_2O_3 substrate, hydrogen atmosphere.

Curve 653747-A

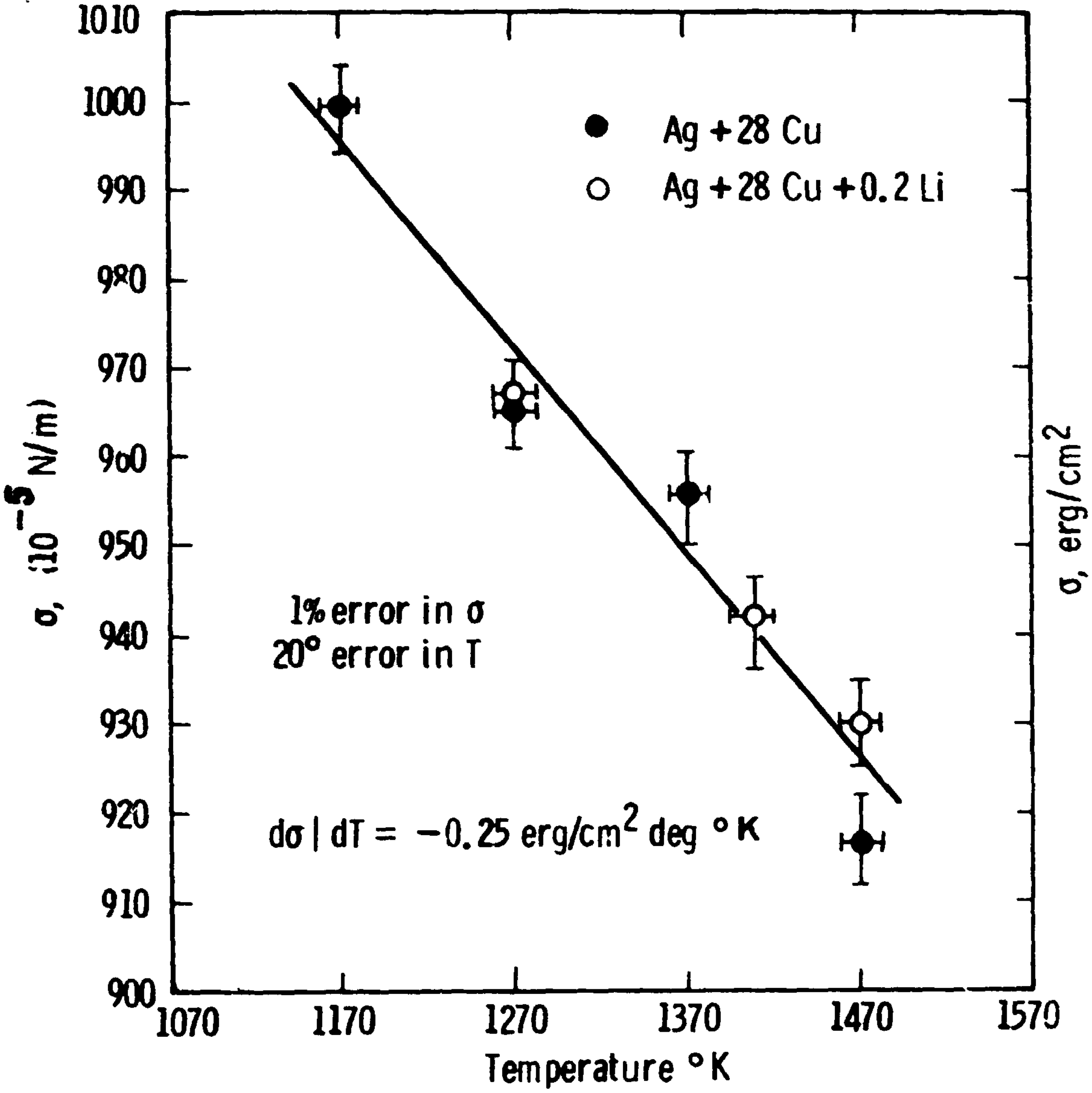

Fig. 2 −Surface energy vs temperature Ag-Cu solder alloys. Al_2O_3 substrate, argon atmosphere.

Curve 653748-A

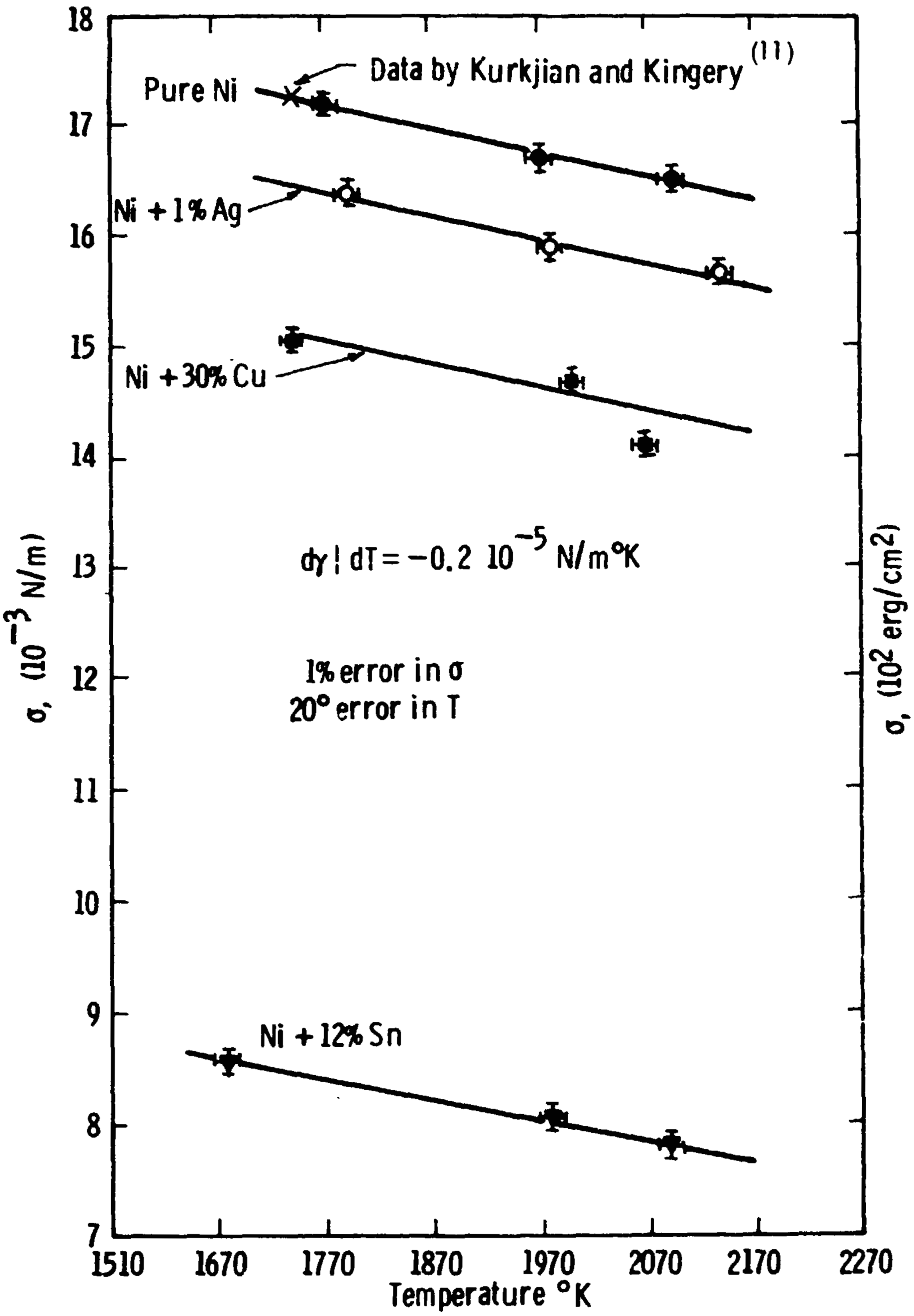

Fig. 3 −Surface energy vs temperature, Ni and Ni alloys, Al_2O_3 substrate, argon atmosphere.

5. SPECIAL SUMMARY: ADHESION-COHESION

A separate Special Summary for each experiment follows which makes a comprehensive review of all adhesion-cohesion phenomena by all investigators on Experiments M551, 552 and 553. Flight and ground base data and observations were compared to identify significant zero gravity effects. A supplementary Special Summary Report will be written for Experiment M551.

Experiment M551 (Metal Melting). This experiment successfully showed the effects of EB melting of three different metals in three modes: 1) cutting, 2) full penetration, and 3) partial penetration. The light, battery powered, 2 kilowatt EB welder unit operated satisfactorily in the Skylab. The concept of the EB unit was by Dr. Bert Schumacher of the Westinghouse Research Laboratory. Under contract of the Process Engineering Laboratory at Marshall Space Flight Center, this EB welder was built by the Westinghouse Astronuclear Laboratory with major inputs from the Research Laboratory.

The most significant result of this experiment was to prove it is both feasible and practical to do EB welding and cutting in zero gravity conditions. Assembly or repair of structures in space are possible. Equal success was seen with Al 2219, SS 304L and pure Ta metals, thus covering a broad range of useful metals. Both EB partial penetration, full penetration and cutting were performed automatically.

The three metal discs involved were automatically rotated at a constant speed in the focus of the low voltage, electron beam (EB) welder unit. The thickness of the discs was machined to increase so that the EB spot encountered a gradually increasing metal thickness with a constant focus and beam power. Thus the EB melting effects went from 1. full thermal cutting to 2. full penetration melting, to 3. partial penetration melting and, finally to 4. a defocussed stationary dwell period.

Adhesion of the melted metals to the adjacent solid metals, and cohesion of the liquid metal to itself appeared to be equally as strong in zero gravity as on earth. Similar cut edge bead periodicity in cut thin plate, and similar periodic "chevron" patterns in full penetration welds were seen. Weight losses are generally insignificant and indicate no weld metal spattering to form droplets.

No microtensile strength measurements were made. However, microstructure examination showed similar metallurgical structures and porosity between zero gravity and ground base specimens. All evidence of solidification effects and movie pictures indicate strong convection currents during welding. Analysis indicates that bulk flow of the liquid (e.g., "sloshing" or cutting) results primarily from a mechanical reaction to vaporization opposed by restoring surface energy forces (surface tension). Convection in the liquid occurs both by bulk flow of the liquid and by a powerful surface energy driven (Marangoni) convection resulting from large thermal gradients in the liquid. Thus, even in the absence of gravity driven (density gradient) convection, strong convection flows occurred. No major zero gravity effect on solidification of "bead-on-plate" welds was seen. A tendency to hot cracking in the case of Al 2219 was observed to be more pronounced in zero gravity.

Although the Experiment M551 was not intended to test weld design configuration, indications are that similar designs and tolerances are required for successful welds in zero gas in a one G environment. Actual welding of two separate metal parts was not attempted, but should be feasible.

Definite adhesion-cohesion phenomena were observed. In the case of the aluminum alloy, quiescent behavior of the weld liquid metal was found at zero gravity. Comparable film studies of welding at one gravity showed marked turbulence. The surface contour of the solidified weld on the beam impingement side is much smoother in the Skylab specimen S/N 129, reflecting less turbulence. This is not attributable to slight differences in weld parameters.

Penetration and cutting of the 2219 aluminum alloy were greater in Skylab testing, but this is attributed to a possibly larger power used in spite of attempts at replication of the power used in ground base test conditions.

The difference in behavior in the cutting mode for the three metals is clearly marked in zero gravity. The melted metal forms a bead on both sides of the cut metal in zero G. In one G it forms a bead on the gravity down side, but in zero G it forms almost equally on both sides of the cut. Surface tension effects apparently predominate in the distribution of the melted metal in the melting mode in zero G.

The oxide film on the aluminum alloy behaved remarkably different in the zero G condition. The oxide film was more continuous and less disrupted in the Skylab specimen. It behaved as a continuous membrane. This is one of several observations indicating less turbulence in the case of the EB melting of metals in zero G.

The tendency for hot cracking of some aluminum alloy welds is well known on earth and may be considered an adhesion-cohesion phenomena. This tendency appeared to be qualitatively more marked in zero G.

The chevron (ripple) pattern onthe weld beads showed a lesser marked and a coarser frequency pattern (notably Ta) indicating lesser turbulence in Skylab specimens.

Weld defects were not as useful in studying gravity effects as anticipated excepting "hot cracking" of the Al 2219. Porosity was infrequent along surface interfaces in the aluminum samples. Cracks occurred only in predictable locations in the aluminum at the weld start, in the dwell area, and at the point where a molybdenum tracer was used. The molybdenum tracer technique itself was overshadowed by the pronounced mixing occurring during welding in this technique.

Weight change measurements generally showed a few milligrams weight loss in both ground base and Skylab specimens in most cases. The hypothesis is the adhesion of the liquid metal to the solid, and the cohesion of the liquid to itself prevented significant weld spattering of weld droplet formation.

In conclusion, the EB melting of these three metals in space indicates that weld penetration can be more uniform, and weld beads more smooth in space at zero G. A greater tendency to hot cracking was noted in the aluminum alloy. Also, the presence or absence of gravity had no significant effect on metallographically observable structure in these three metals.

Experiment M552 (Exothermic Brazing). This experiment was particularly successful in showing the effects of zero G. It was also the first radioisotope experiment in space. It provided the technical basis for a very practical method of joining structural members in zero G space environment. Based upon these preliminary results, it appears that brazing is easier in space. Dimensional gap tolerances are larger.

This experiment has shown that capillary flow of the braze alloy can occur in relatively wide gaps in zero G. Specimen SLS-3 had a 0.020 inch gap and SLN-4 had a tapering gap from zero up to 0.030 inch. True capillary flow occurred in these relatively wide gaps. Commercially, braze gap tolerances rarely exceed 0.005 inch. Increasing the allowable tolerances for gap in joints greatly increases the applicability of brazing to joining of structures in space. The practical use of stored chemical energy in a Thermite type heating unit, electrically ignited, for accomplishing the braze heating cycle was well demonstrated.

The radioisotope tracer test, proposed by this investigator, yielded very interesting results. The specimen configuration is diagrammed in Figure 4. Oak Ridge National Laboratory developed the technique and performed all tracer evaluation. This important tracer mapping technique showed a definite difference in the flow patterns of the braze alloy on earth and in space.

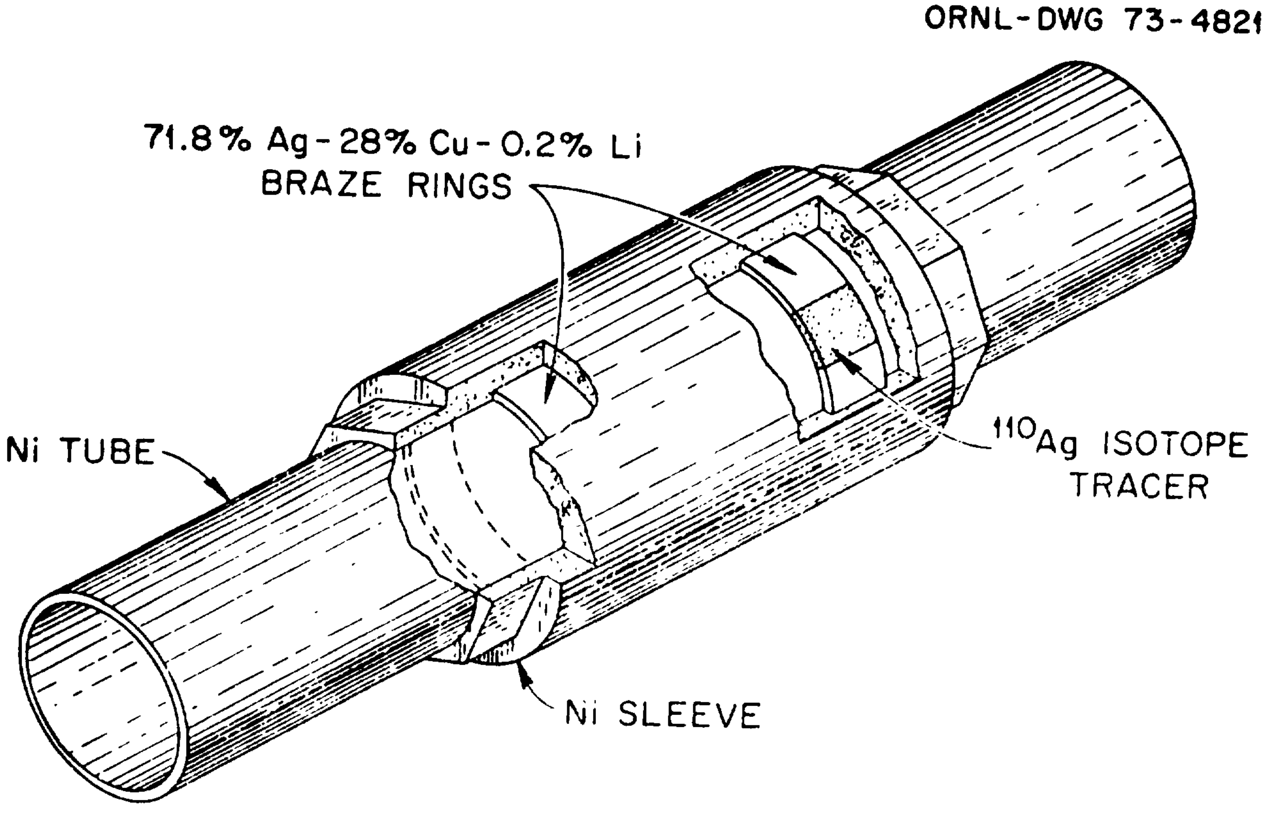

Figure 4. M-552 Experiment Braze Assembly

The effects of one G were evident for both the horizontally and vertically brazed samples. Both samples MCN-1 and MCN-3 were brazed horizontally and were left with fillets of braze containing the radioisotope tracer at the bottom of the braze ring groove in which the tracer pellet was originally located. In a sense, gravity and capillarity were competing forces in the one G brazed experiments; gravity tended to "puddle" the braze alloy at the bottom of the ring groove, while capillarity tended to pull the braze into the narrow annulus. The effects of gravity can also be seen in the radioactivity intensity maps for samples IMN-2 and MCN-4. The tracer alloy in these two taper-gap samples, brazed in a vertical position, was contained within a definite braze line around the interior of the annulus. This braze line or "water level" line was a direct result of gravitational force.

Thermal history associated with the braze assembly had a subtle but important effect on the flow of the isotope tracer. In all one G experiments there appeared to be a strong tendency for the tracer braze to flow more circumferentially than longitudinally inside a narrow annulus. This characteristic was especially evident for samples MCN-1, IMN-1, and MCN-4. It would seem that the flow of tracer braze was influenced by thermal gradients which existed, at least initially, during the melting of the alloy. Existence of these thermal gradients might well have been caused by the manner in which the exothermic material was ignited, i.e., through the use of two electrical igniters. For the one G tests, these igniters were located at the tracer-pellet end of the assemblies, at azimuths of 90° and 270° from the original pellet location (0°). These regions would reach the melting point and spreading temperature of the braze alloy, as well as their maximum temperatures, well before other areas of the assembly reached equal temperature levels. Braze alloy would flow into these regions of highest temperature before flow could occur in the cooler regions during the initial period of the exothermic heat source burn. It is well known, from a practical standpoint, that a braze alloy will flow into areas of higher temperature.

The effect of a small increase in temperature upon the rapid spreading of the braze alloy was noted in ground base testing.

No attempt was made to use a "dry hydrogen" atmosphere. The atmosphere was a nominal vacuum, and the contaminant gas was largely hydrogen from the exothermic unit.

Radioisotope tracer mapping of Skylab samples SLN-2 and SLN-4 showed very interesting differences and similarities when compared with similar maps of ground base samples. One significant difference was the enhanced braze alloy flow (with subsequent increased movement of tracer alloy) observed in the samples brazed in space under zero G conditions. Radioactivity was observed for both samples SLN-2 and SLN-4 well outside of the ferrule region on the tracer pellet end. With gravitational forces absent, capillarity of surface forces was unopposed, resulting in rather dramatic increased flow of the braze alloy. Another difference is due to the absence of gravity manifested in sample SLN-4, a taper annulus sample, which demonstrated the absence of a braze "leveling" effect noted or ground-test samples; islands of braze alloy filled regions having very large gap widths. In some respects, the radiation intensity maps for the Skylab samples SLN-2 and SLN-4 were very similar to those obtained from earth samples. The tracer alloy moved initially towards the thermally hot regions near the igniters. In the Skylab flight package, the igniters were located near azimuth locations of 45° and 225° with respect to the tracer pellet location at 0°. In tracer maps, virtually all of the radioisotope was found in regions between an azimuth of 45° and 225°. Braze fillets containing ^{110}Ag that remained in the braze ring grooves of sample SLN-4 cannot be explained by gravitational effects, as in the ground samples, and must be a result of surface energy forces.

It is interesting to note that the areas void of solid braze alloy, yet wet by molten braze material, showed no residual tracer isotope activity. This observation would imply that the silver did not react nor adhere to the nickel surface. Analysis showed the remaining film of braze after draining is mostly copper.

The addition of a radioisotope tracer to the M-552 brazing experiment provided a unique picture of the thermal history of braze melting within the annulus as well as a useful representation of the braze alloy flow pattern during the melting-solidification process.

The sectioned specimens were examined to see if the menisci of the solidified braze alloy revealed information on the behavior of liquids adhering to and flowing upon solids in zero G. The conformance of the meniscus surface with theory supports the conclusion that the liquid-vapor surface tension is substantially uniform. This is of importance because the surface tension is quite sensitive to variations in temperature and surface composition.

An increase of flow of the Lithobraze BT (71.8% Ag, 28% Cu, 0.2% Li) was achieved in space. Alloy flow patterns, observed in samples brazed in a zero G field, extended beyond the ferrule annular region, while patterns observed in samples brazed in a one G field were totally contained within the annulus.

The amount of braze alloy in specimen SLS-3 was insufficient to fill the uniform 0.020 inch gap. Thus, a "starved" joint was formed. Because of the forces of wetting and spreading, the liquid tended to penetrate to positions of minimum gap clearance, although the capillary flow in the wide gap was complete.

Surface tension theory indicates that the hydrostatic pressure (due to adhesion) in the liquid near a small gap is less than that near a large gap. In a complex capillary system, this pressure difference will tend to drive the liquid from wide gap to narrow gap locations. These effects can be seen in "starved" joint conditions such as SLS-3. This movement of the liquid to narrow gap locations is driven by surface energy forces of adhesion and cohesion.

Capillary action was concluded to be the main force in the movement of the molten braze alloy from the braze ring grooves into and around the annulus formed between the tube and ferrule. Capillary forces depend mainly on the gap width, surface tension of the liquid braze, viscosity of the liquid braze, wetting angle, and metal surface condition.

The absence of gravity greatly extends the scope of brazing, and, thereby, the applicability of brazing to fabrication in space. In zero gravity environment, the surface tension forces begetting capillary flow are unfettered, while on earth these forces must compete with gravity. Study of braze alloy distribution in Skylab specimens clearly indicates that dimensional tolerances, especially braze gap clearances, will be far less critical to joining operations in space than on earth. The practical significance of this fact, which had been predicted but never tested, can hardly be overemphasized. In space fabrication, many joints, which on earth would be produced by welding, could probably be brazed.

Experiment M553 (Sphere Forming). One of the three experiments, M553 (Sphere Forming) is based upon the tendency of a freely drifting liquid drop to form a sphere in zero G.

There is a remarkable tendency of a liquid drop to form a sphere when drifting in a zero G environment. High speed movies (240 frames/second) show the EB melting and deployment of liquid metal drops formed from 6 mm (0.25 inch) diameter short cylinders of pure metals and alloys. The high speed movies were taken in ground base tests (one G) and KC-135 jet parabolic flights (zero G). Lower speed movies (24 frames/second) were taken during the Skylab flight tests. During melting and upon deployment, the liquid metal surface modulates and the drop shape oscillates. In free drift after deployment, the drop is still changing shape as it moves out of camera range. If the drop were to remain liquid long enough for the internal fluid flow to dampen, it seems that a liquid sphere would form as predicted.

None of the solidified drops was quite spherical. Most drops are approximately axially symmetric. Their surface morphologies are definitely not as smooth as a polished ball bearing, as a result of crystal growth during solidification (the subject of a separate Special Summary Report).

Deployment of the liquid drops into a free drift condition was resisted by adherence of the liquid to the pure alumina pedestals. The much larger forces tending to deploy the drops resulted from vaporization momentum reaction at the EB impingement spot, and from the effects of the mechanical spring compressed on a wire ("sting") attached to the short metal cylinders. Deployment velocity was great enough to reduce drift time and not allow solidification in a free drift condition. The work of adhesion of the liquid drops to the alumina pedestals was calculated from the measurements of surface energy and liquid/solid contact angles. The values are small, and the excess kinetic energy to deploy the drops is attributable to the mechanical reactions to sideward impingement of the EB. A vaporization momentum reaction produces a force pushing the drop in the direction of the EB. Analysis by this investigator indicates that in future work the EB direction should be perpendicular to the alumina pedestal surface. Then the vaporization force will tend to keep the liquid metal drop on the pedestal till completely melted and ready for deployment. The mechanical reaction to EB cutoff can be used for the controllable deployment force.

Of the four metals tested, the Ni-12Sn alloy showed a lower surface energy than the other three (Section 4). The calculated work of adhesion to the alumina pedestal was much lower for this alloy. This did not affect the force of deployment since the forces causing deployment were apparently excessive.

Of the twenty specimens which were melted and solidified, either deployed or retained, several showed roughly spherical shapes as expected in the near absence of gravity. Generally, axisymmetric shapes were observed. Many of the drops show the strong effect of the liquid metal volume decrease on solidification. One drop had a large internal void, and several had "shrinkage voids" formed by solidification and shrinkage of a liquid within our already solidified shell.

Although none of the samples solidified as spheres, some retained an area which was not melted or a protuberance at the sting area which never melted. They either solidified prior to release or solidified so rapidly after release that the protuberance did not have time to conform to sphericity prior to solidification.

Although this liquid metal drop deployment technique is difficult to control, particularly with respect to deployment velocity, evidence indicates that nearly perfect spheres can be formed by solidifying non-crystalline (glassy) materials as freely drifting liquid drops if sufficient time is allowed to dampen surface undulations and shape oscillations.