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THE SATURN V SPACE PROGRAM AND ALUMINUM WELDING TECHNOLOGY

By

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To say the facts are incomprehensible is a rationalization of individual ignorance [1].

But we are not likely to find science returning to the crude form of causality believed in by Fijians and philosophers, of which the type is 'lightning causes thunder' [2].

Science, in other words, is a system of relations [3].

The characters which science discerns in nature are subtle characters, not obvious at first sight. They are relations of relations and characters of characters [4].

Rather against my better judgement I will try to give a rough impression of the theory. It would probably be wiser to nail up over the door of the new quantum theory a notice, 'Structural alterations in progress - No admittance except for business,' and particularly to warn the doorkeeper to keep out prying philosophers [5].

INTRODUCTION

The exploration of space may but be a part of man's search for himself. Not content to speculate on his orgin and fate while bound by gravity and the cocoon of the earth's atmosphere, he must escape into the vast universe in his attempt to 'become' [6]. He has assumed his existence, skeptical as he may be, and is striving to formulate his essence, to mature, to become an autonomy. A. Korzybaki called it the "manhood of humanity" [7].

Space exploration is not accomplished by wistful thinking and intense desire alone. Artifacts, tools, and transportation vehicles are brought about by scientific and technological activity. As in other escapades of curiosity, man derives by-products of knowledge in technology that are beneficial in respect to peaceful coexistence and biosocial well being. I refer specifically in this discussion to fringe benefits for industry in the area of welding technology. The welding techniques, processes, and equipment that are used to produce space vehicles of high structural reliability can also be used to make better and more economical products necessary in our more mundane existence.

Even more specifically, I refer to the welding of certain aluminum alloys. I proceed to speak, then, of the welding dilemma, a resulting weld development complex, and the growing data in welding technology.

THE WELDING DILEMMA

Today, two major means of non-destructive inspection of welds are x-rays and visual, microscopic examination. X-rays are usually two-dimensional, hardly adequate for plate weldments. Visual examination, more often than not, reflects the limits of our nervous systems in perceiving the world outside our skins and, if we but listen, may tell us more about ourselves than about the world. Certainly, we cannot visually perceive the effect of energy on mechanical strength; nor can we place a quantity on residual stresses. It would take x-ray and microscopic vision to see element precipiatation, copper migration, etc.

Herein lies the dilemma in welding space vehicle structures. The burden of reliability rests with welding techniques and processes. Obviously, this implies a knowledge of processes and the consistency of their effect on materials. Unfortunately, such is not always the case. Welding is yet more art than science.

"A weld may be defined as a continuous defect surrounded by parent metal," is a statement familiar to people at the Marshall Space Flight Center. The statement "is not meant to be facetious nor disparaging; rather it expresses acceptance of a problem, and thus places the engineer in the favorable position of emotionally unhindered investigation" [8].

In many ways, the space age has stimulated engineers to improve techniques and equipment. But all is not rosy; problems still exist. A major current problem is the high incident of weld defects and subsequent repairs. Of the many defects encountered, porosity is outstanding (Table 1). In 144, 000 inches of weld made on four Saturn V first stages, porosity accounted for 79 percent of the total number of defects. Cracks ranked second at 9 percent. If defects were dispersed equally, only 0.022 of a defect would occur per inch of weld. Nevertheless, we had repairs, a fact that is somewhat disconcerting. Not only are defects not uniformly distributed but also one is not able to predict when and where they will aggregate.

Repairs at best are a poor solution to the problem of defects, and to continue to indulge in the practice seems a "rationalization of ignorance." There are so many voids in our knowledge of the effect of repairs on joint performance. We have no adequate means of measuring residual stresses, no clear picture of strength versus multiple fusion and microstructural changes; and we have an uncontrolled, non-uniform energy input, particularly in hand repairs. But repairs are simply an exaggeration of an ever present problem --- the continuous defect.

TABLE I. DEFECT FREQUENCY

Type of Defect	Number of Defects	Percentage of Total
Arc Burn	5	0.15%
Underfill	15	0.46%
Inclusion	46	1.40%
Miscellaneous	117	3.57%
Mismatch	206	6.28%
Crack	287	8.75%
Porosity	2604	79.40%

Total Defects = 3280 $\frac{\text{Total Defects}}{\text{Inches of Weld}} = .023$

A DEVELOPMENT COMPLEX

Such problems have led us back to the laboratory. We are convinced that a more scientific approach is essential if we are to free welding from its cocoon of black magic and subjectivity. To this end we are engaged in basic interrelated studies of aluminum welding, a joint effort of MSFC and industry.

We are fully aware that a welding process is a dynamic whole, an entirety. It is a series of interrelated, interdependent events. We are not able to minutely analyze the dynamic whole, but must arbitrarily select restricted areas for study, which might be considered fragments of the map of welding.

The time comes, however, when the fragments must be integrated and the whole map constructed, if we are to understand welding and if we are to formulate process control. Some fourteen such MSFC funded studies are being integrated by Dr. Masubuchi of Battelle Memorial Institute of Technology. The first report will be available to the public in July, 1967 [9].

The studies are directed toward four major areas of interest (Fig. 1), i.e., porosity, metallurgy, time-temperature or power density, and contour control.

Preventing porosity, the most common of weld defects, logically starts with learning its source. From a quantitative study of contaminants in helium shielding gas, a tentative guide has been established for space vehicle fabrication. I say tentative because it is based on welds made in an atmosphere controlled chamber, not in open air. The guide shows concentration levels where significant changes occur (Fig. 2). Weld density begins to increase with 250 ppm of oxygen and to decrease with the same amount of hydrogen; porosity begins to occur with 350 ppm; the welding arc begins to waver at 800 ppm, etc.

The same investigators have calculated that an influx of 0.6 percent of air saturated with water vapor would result in 250 ppm of hydrogen in the shielding gas.

Less than 1 mg/in of hydrocarbons on the material surface is considered necessary to generate 250 ppm of hydrogen in the shielding gas. A single fingerprint

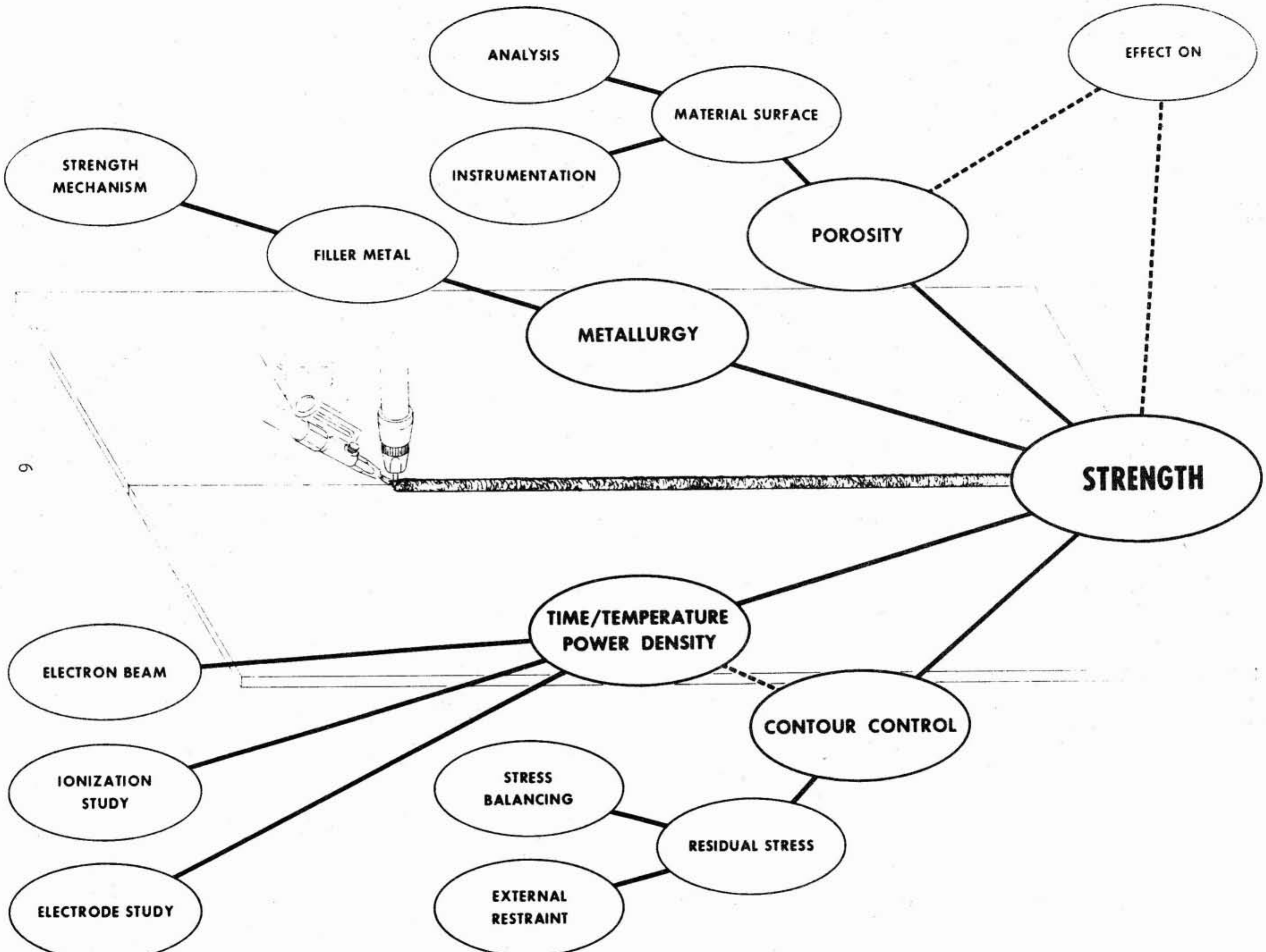


FIGURE 1. DEVELOPMENT AREAS

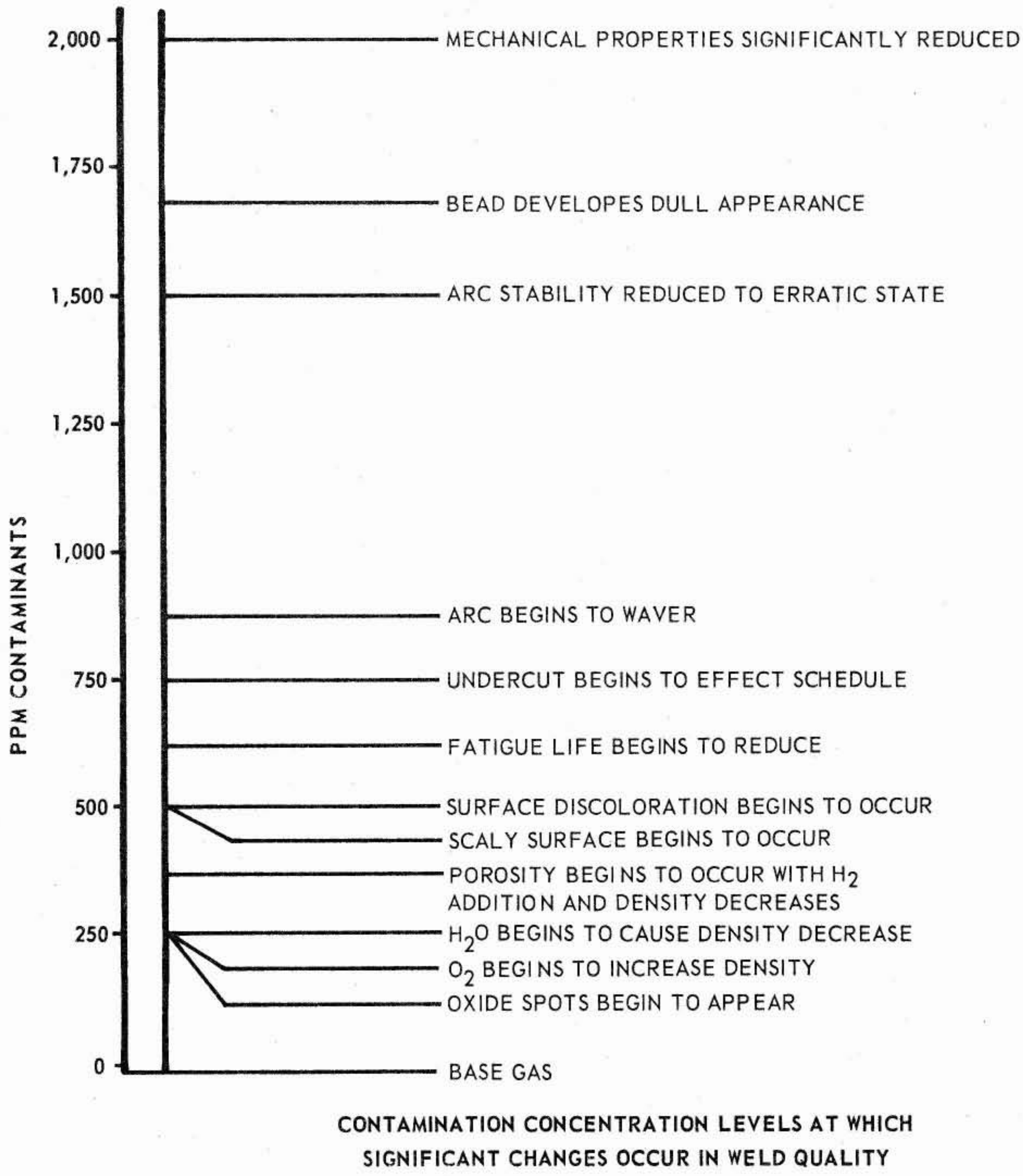


FIGURE 2. CONTAMINATION GUIDE

could cause 750 ppm hydrogen increase. These calculations indicate that a very small amount of organic material can be a serious factor in causing porosity.

It is highly probable that contaminants on the aluminum surfaces are the greatest source of porosity in welds. Researchers are now concentrating on the identification and classification of such contaminants. They are using several methods of surface analysis, such as spectral reflectance, radiactive evaporation, gas chromatography, mass spectrometry, and spark emission spectroscopy.

"As machined surfaces result in defect - free welds. All other treatments induce some degree of weld impairment"[9i]. Figure 3 is a non-quantitative scale of this. Machine surfaces have zero defect - potential. Increasing in potential are specimens 10 percent chemically cleaned and water soaked, chemically cleaned plus water storage, benzene degreased, anodized (according to time), and silicone coated.

The areas of metallurgy and time-temperature characteristics are equally important. Welding energy input, that is the time duration and the amount of energy to which a material will be subjected, can be correlated to strength. This is more clearly seen in welds made on 2219-T87 al alloy plate. Levels of energy, expressed as joules per inch of travel per inch of material thickness, or joules/in.^{2}, result in corresponding levels of strength (Fig. 4). Thus, 40,000 to 100,000 joules/in.^{2} show a plateau of 37,500 to 42,000 psi ultimate strength. As joules decrease, strength sharply rises. 10,000/in.^{2} produce strengths as high as 57,000 psi: 2219-T87 base metal has a strength of 69,000 psi. About 10,000 psi of this strength is due to strain

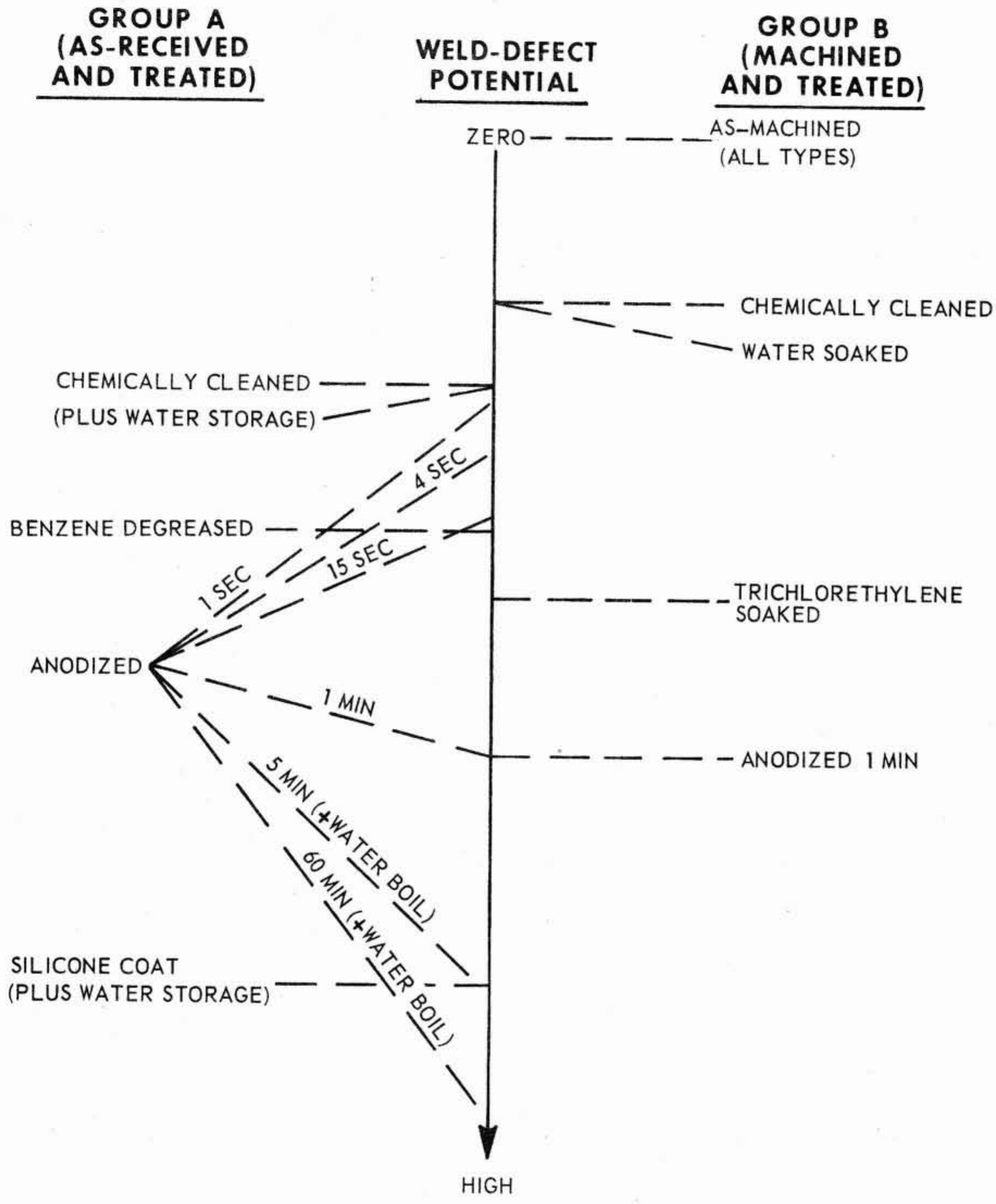


FIGURE 3. DEFECT POTENTIAL

hardening. The unstrained condition, T-62, is listed at 59,000 psi, nearly reached in electron beam welds of 10,000 joules/in.^{2}

The effect of energy is also seen metalurgically. As joules increase there is an increase in grain size and in Θ or copper aluminide agglomeration at the grain boundaries (Fig. 5). The strength versus energy curve has a steep slope from 30,000 to 10,000 joules/in.^{2} Perhaps this is related to a marked decrease in the excess energy over that required for activation of copper migration. But metallurgy may not provide a complete explanation of energy versus strength. Width of weld nugget, if flush, also correlates with strength. We have yet to learn more of the mechanics of weld failures. Nevertheless, both weld geometry and metallurgy are to a great extent determined by the amount of welding energy, more specifically, by the arc power density.

It is through such studies as these, and through manufacturing experiences, that welding technology will most benefit.

APERCU'

And so I come to that blunt and rather disconcerting question, "What has the space program contributed to welding technology?" I say disconcerting because many of the contributions are quite subtle, beyond the reach of symbolism, and often never recognized. In addition, the space program is quite complex and involves many different materials and modes of joining. I can speak only of gas tungsten arc, gas metal arc, electron beam welding processes, and of our adventures in manufacturing the Saturn V space vehicle.

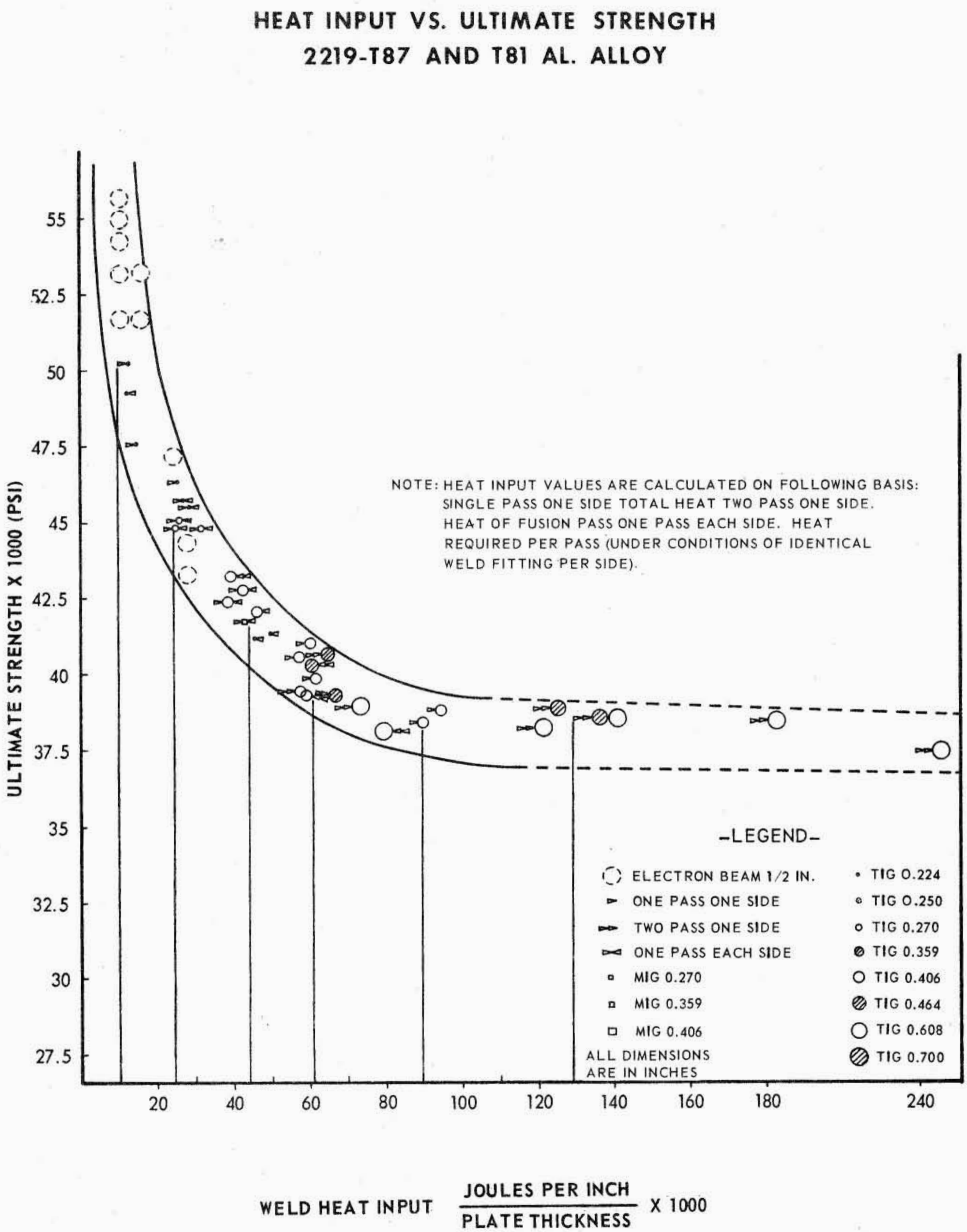
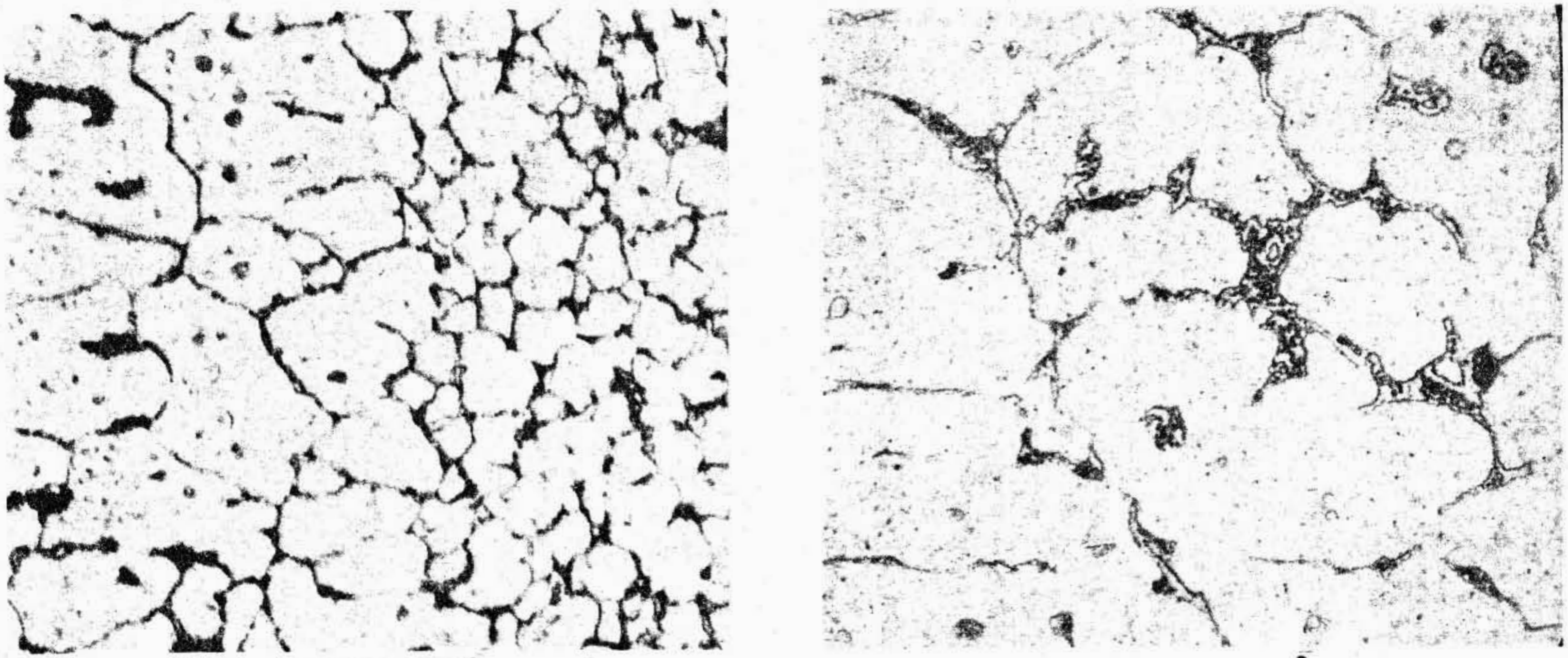


FIGURE 4. 2219-STRENGTH VERSUS ENERGY



20,000 JOULES/M^2
1,000 X FUSION TIME

80,000 JOULES/IN^2
1,000 X FUSION TIME

FIGURE 5. 2219 MICRO-STRUCTURE VERSUS ENERGY

The following contributions are clearly identified and can be adequately described.

Assembly Concepts

The event of the Saturn V vehicle, 33 feet in diameter, more than four times the size of the Redstone Missile, forced a change in assembly concepts. It became necessary to erect the containers with the center axis in the vertical position. Welding techniques had to be extended to horizontal and vertical modes, seldom used in high quality aluminum welding. But jigging accuracy requirements did not lessen. Mating of parts, distortion control, etc., were just as important in large as in small vehicles.

New concepts were in order, concepts that would provide simplicity, economy, and versatility. In general, a new philosophy was evolved which (1) placed greater responsibility on electronic and welding equipment, thus allowing less complex and less accurate tooling, (2) omitted superfluous tooling details not really pertinent to functional requirements, and (3) stimulated new or different tooling and welding concepts.

The weld jigging most often used consists in round-out rings, and rigid clamping members (Fig. 6). Such jigging serves a two-fold purpose: to support the molten weld puddle (often to control solidification), and to forcefully maintain alignment of the parts being welded. The extension of this concept to large diameter tanks is expensive and difficult to accomplish.

An alternate procedure is to use local jigging, intermittent tack welding, and free state welding. Free-state welding, i.e., welding without puddle support, became

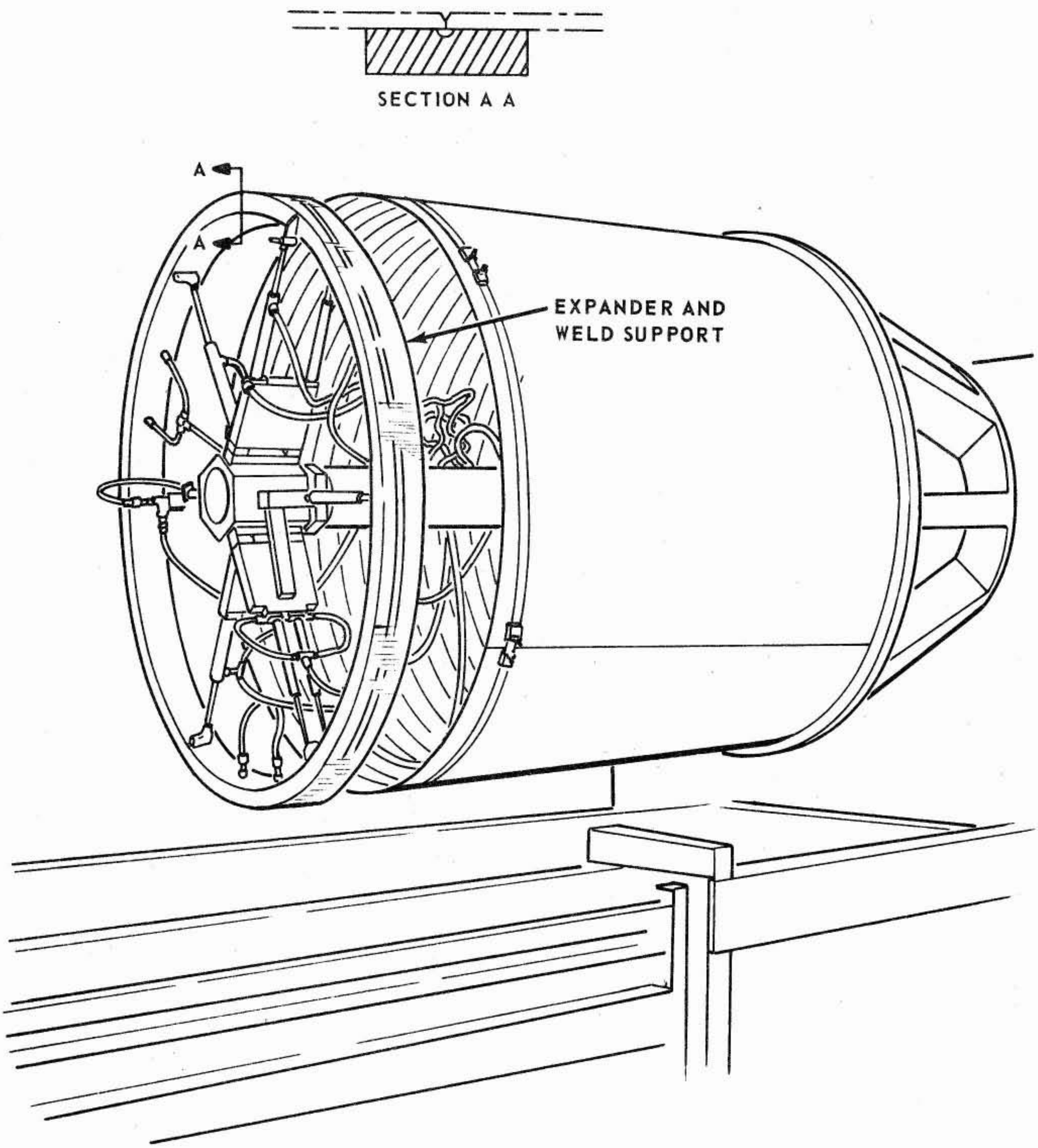


FIGURE 6. CONVENTIONAL WELD-JIGGING

practical, through improved power sources and electronic controls, in materials as thin as 0.125 in. But removing the puddle support only insured more uniformity of solidification, and did not lessen parts - alignment requirements. The old principle of strap clamps, not unknown in large tank construction, is effectively used to align parts. A number of these devices may be applied at intervals around two cylinders to be joined (Fig. 7).

The theory of operation is that of a simple compressive mechanical device, with the two basic parts located on opposite sides of a weld joint, and drawn together by tightening the thin band until the work pieces are aligned.

Alignment is maintained during welding by tack welds, made before removing the strap clamps. The combination of strap-clamps, tack welds, and precision weld equipment constitutes a joining method that is economical, versatile, and accurate [10].

Reduction of Porosity in Aluminum Welds

From the basic studies previously noted, we have fairly conclusively determined that material surface contamination is the major source of porosity in aluminum welds. The nearly zero-defect potential method of preparing material for welding is simply metal removal. Two approaches are used. First, metal can be scraped or machined before parts are jigged. In assembly of large components many hours will elapse between start of jigging and welding. It is essential, then, that meticulious care be taken not to recontaminate the material. If, however, welding is done from each side of a joint the surfaces can be prepared just before welding by machining small grooves (Fig. 8).

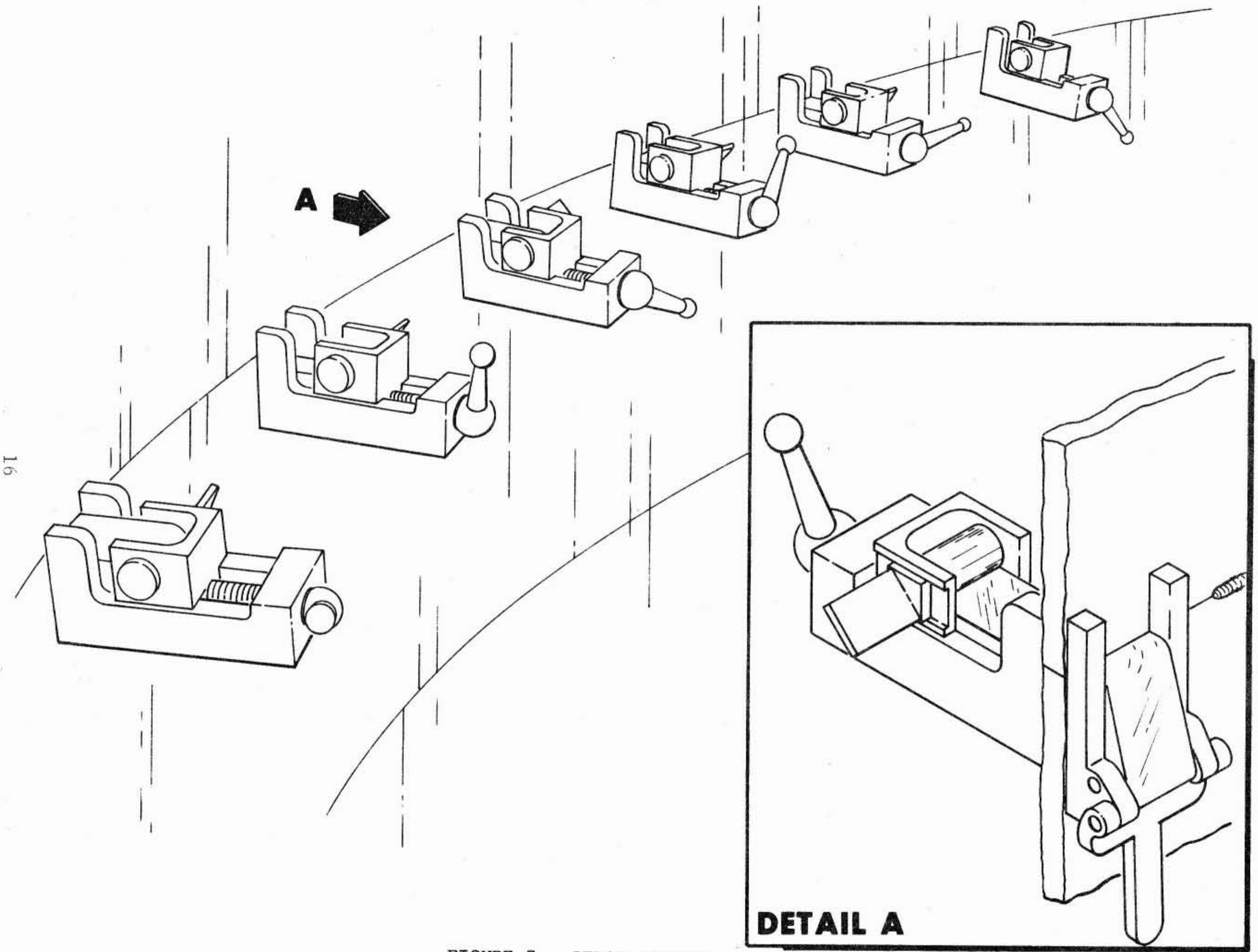


FIGURE 7. STRAP CLAMPS

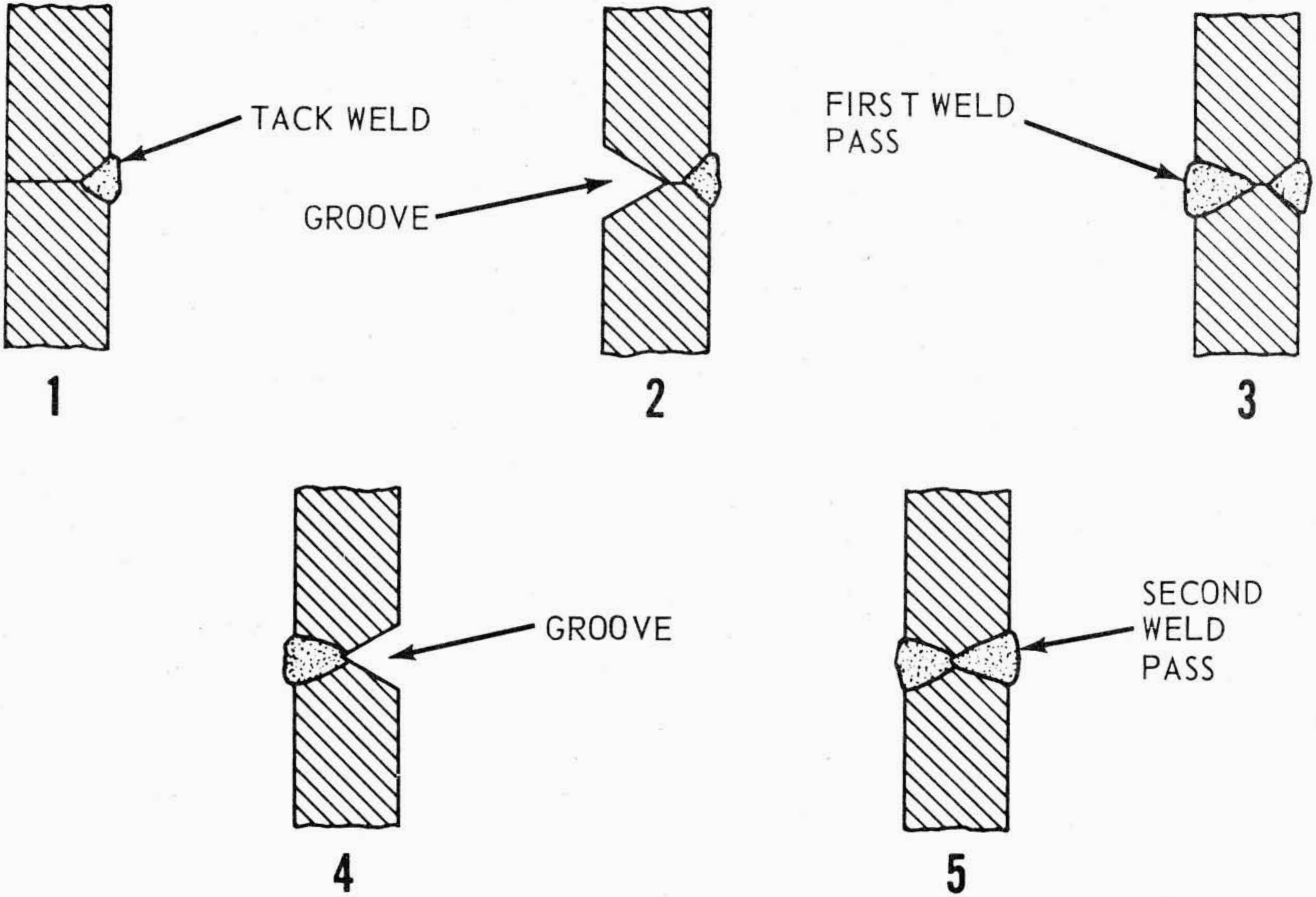


FIGURE 8. POST-JIG WELDING

Discriminate Use of Energy in Welding

As shown in time-temperature studies, the metallurgical quality of welds can be improved and strength can be controlled by discriminate use of welding energy (Figs. 4 and 5). In addition, porosity frequency, location, and size can be correlated with time-temperature (Fig. 9). As the travel speed is increased (with correspondingly less energy input), the porosity frequency drops and porosity location moves toward the center of the nugget suggesting that porosity is being arrested in its formation. At some level of reduced time-temperature, porosity should be almost entirely stopped, or at least so finely distributed that it would not be discernable.

The next logical step is to increase process power density so that welds can be made at low energy levels. This is already possible in electron beam welding. However, this process has been limited in application because of its high vacuum requirement (10^{-5} torr). Three approaches are being taken to remove this limitation. In progression, they are as follows:

1. Split, or Local, Chamber Concept. A conventional high-vacuum chamber often is impractical if large components must be completely enclosed. The split chamber, with adequate local sealing, reduces the chamber size to that necessary to encompass the weld joint (Fig. 10). The welding of fittings into bulkhead gore segments, for example, would eliminate the severe distortion and buckling which result from the high energy gas tungsten arc (GTA) process.

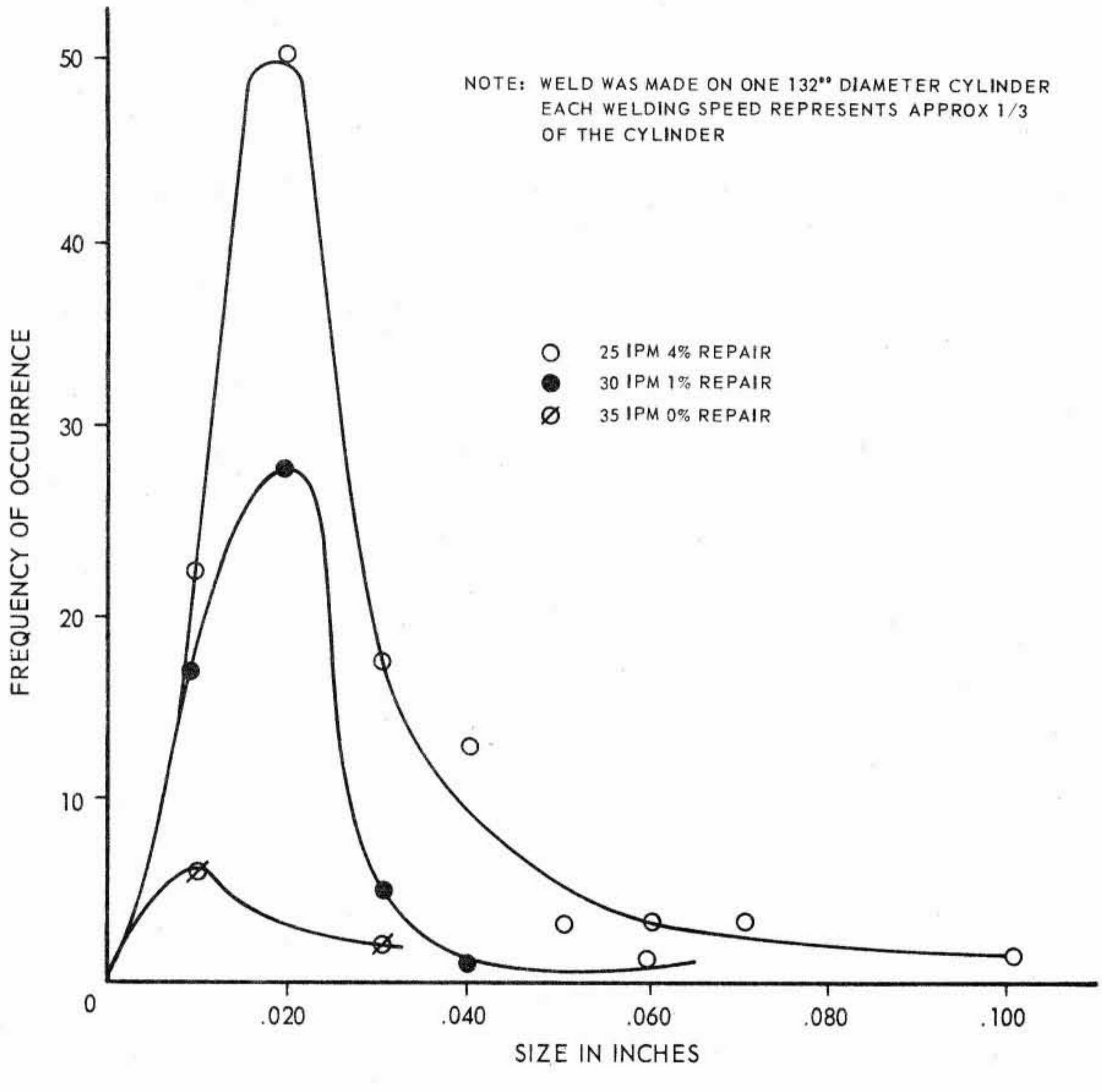


FIGURE 9. TRAVEL SPEED VERSUS POROSITY

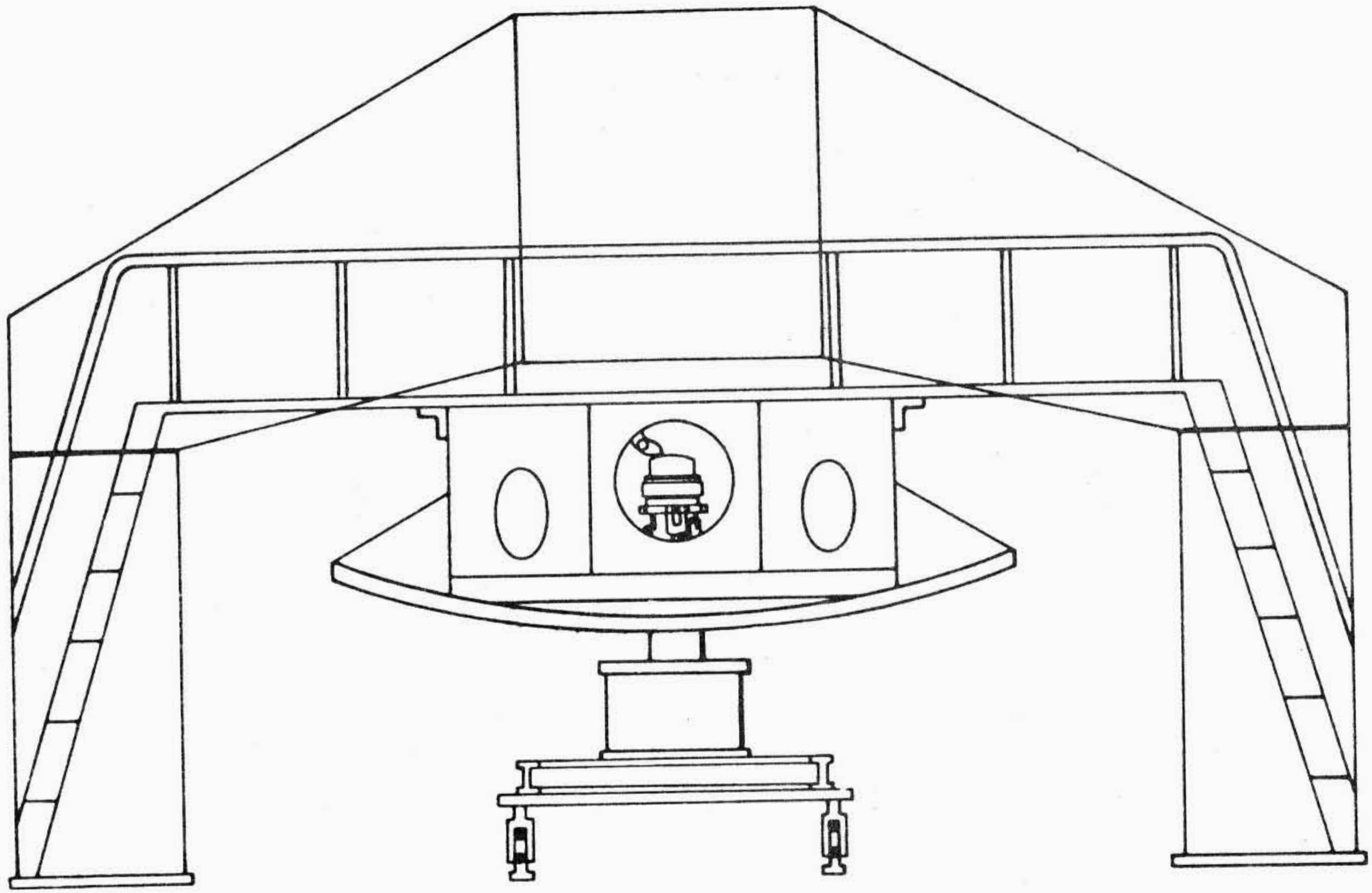


FIGURE 10. SPLIT CHAMBER

2. Plasma Electron Beam Welding. The plasma electron beam (PEB) system uses a simple, hollow electrode gun which will function in a vacuum of 10^{-2} torr. Welding joint efficiencies have been similar to those produced in high vacuum. The PEB system can also be combined with the split-chamber approach to increase the potential of versatility.

3. Non-vacuum Electron Beam System. The most direct approach toward versatility is to remove the vacuum chamber requirement. Such a system exists, and currently is being improved and refined for selected application studies (Fig. 11). The vacuum is maintained within the gun as the beam passes through a series of orifices which separate the differentially evacuated compartments. Helium gas is introduced outside the last orifice to minimize beam scatter.

HOW, NOW?

Always we go forward. From the mistakes of yesterday, from the clarification of problems, and from each bit of progress come the maps for tomorrow's research (Fig. 1).

In the case of aluminum alloy, we need to learn more of the effect of energy on material, i.e., the structural mechanism of strength in base metal, and the structural changes caused by different time-temperature histories. We need to concentrate on methods of material surface preparation just before or during welding, and on devices for measuring the degree of cleanliness of surfaces. We need to perform analytical and emperical studies of local distortion, buckling, and joint offset caused by thermal expansion and contraction. We need to further correlate weld defects to joint performance, and to invent means of non-destructively inspecting for strength, stress, microstructure, etc.

Welding is a tool that is coming into its own, an emerging science that has been greatly stimulated by the space program. I predict that it will continue to emerge at an increasing rate.

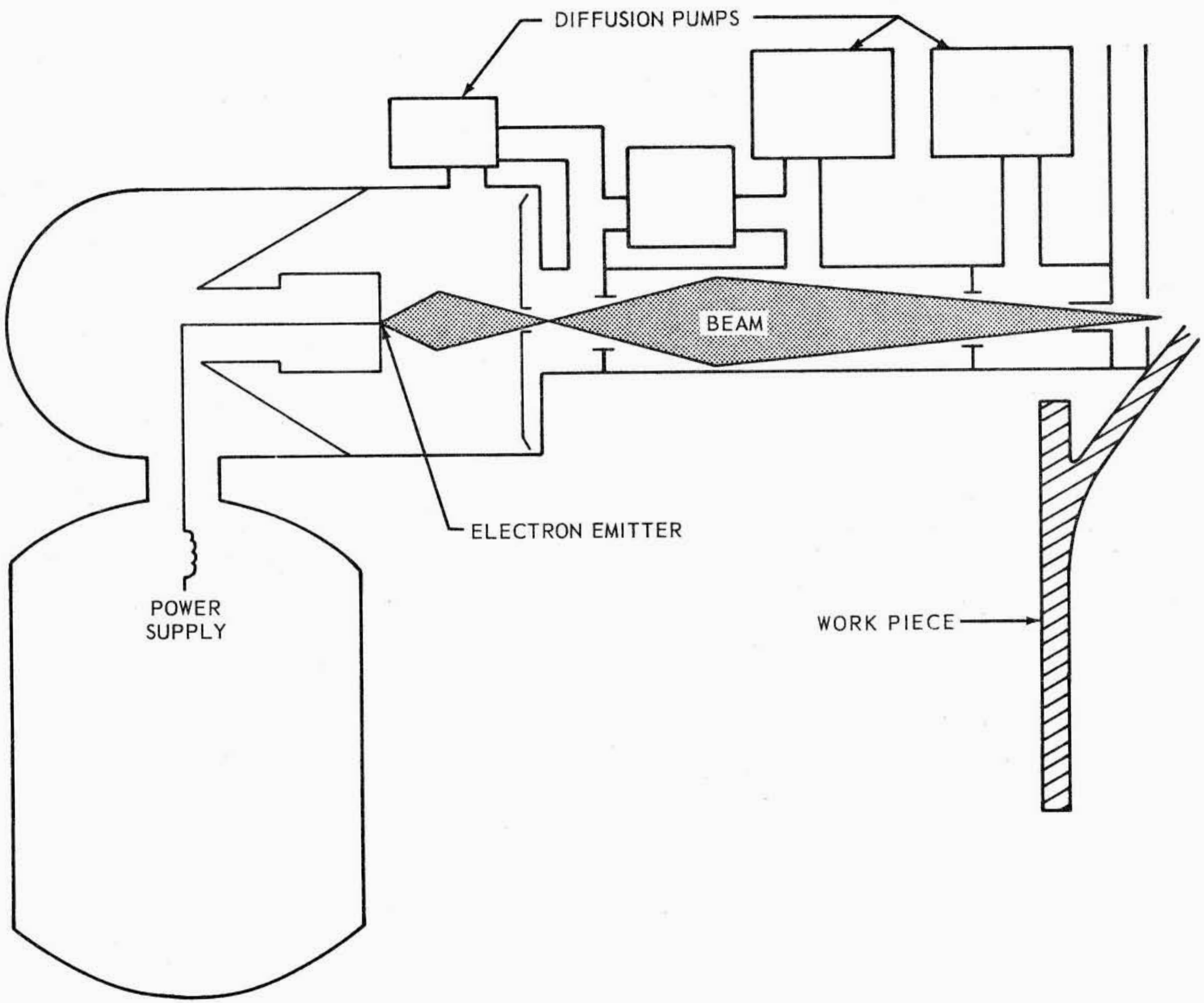


FIGURE 11. NON-VACUUM ELECTRON BEAM WELDER

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