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A PATH TO IN-SPACE WELDING

and to other In-Space Metal Processing Technologies

Using Space Shuttle Small Payloads

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ABSTRACT

As we venture into space, it becomes necessary to assemble, expand, and repair space-based structures for our housing, research, and manufacturing. The zerogravity-vacuum of space challenges us to employ construction options which are commonplace on Earth. Rockwell International (RI) has begun to undertake the challenge of space-based construction via numerous options, of which one is welding. As of today, RI divisions have developed appropriate resources and technologies to bring space-based welding within our grasp. Further work, specifically in the area of developing space experiments to test RI technology, is required.

RI Space Welding Project's achievements to date, from research and development (R&D) efforts in the areas of microgravity, vacuum, intra- / extra- vehicular activity and spinoff technologies, are reviewed. Special emphasis is given to results from G-169's (Get Away Special) microgravity flights aboard a NASA KC-135. Based on these achievements, a path to actual development of a space welding system is proposed with options to explore spinoff in-space metal processing technologies. This path is constructed by following a series of milestone experiments, of which several are to utilize NASA's Shuttle Small Payload Programs. Conceptual designs of the proposed shuttle payload experiments are discussed with application of lessons learned from G-169's design, development, integration, testing, safety approval process, and KC-135 flights.

INTRODUCTION

In recent decades, welding has become the dominant process for building metal structures on Earth. The rapid and continuing growth of welding applications is due to the inherent advantages of this metal joining method over the mechanical fastening and bonding techniques. The advantages of welding include higher joint strength and rigidity with reduced joint mass, increased design flexibility and simplicity of structural joints, more reliable hermetic sealing of pressurized structures, and broader versatility for emergency repair. These benefits dramatically reduce construction costs on Earth, and seem to be even more attractive for space-based applications. For these reasons, welding has been identified by NASA's Pathfinder Initiative as a critical enabling technology for in-space construction capabilities. There is no doubt that NASA's aggressive space exploration program for the next 30 years, which includes a permanently manned space station, a lunar base, and a manned mission to Mars, will all dramatically benefit from an in-space welding capability.

R&D ACHIEVEMENTS TO DATE

As of today, RI divisions have developed appropriate resources and technologies to bring space-based welding within our grasp. In-space welding, unlike terrestrial welding, constrains us with low or no gravitational forces in an environment which includes both pressurized-intra-vehicular operations and vacuum-extra-vehicular operations. Through internally funded programs and NASA funded contracts, RI has conducted research and developed technologies which address various constraints associated with in-space welding.

WELDING PROCESS SELECTION

Any terrestrial welding process modified for space-based applications should be amenable to both manual and automatic operations, and have the extra versatility to function inside pressurized life supported compartments as well as in the outside vacuum. Zerogravity should not pose any fundamental problems with the process. The process must conform to rigid safety standards; it should produce optimum quality welds on all aerospace metals; it must operate with available power levels and efficiently utilize energy; it should be forgiving of joint mismatch or fit-up problems; and it should use a minimum weight of consumable materials. However, to choose one <u>single</u> welding process, which maximizes each of these many requirements, is practically impossible. Thus, it is necessary to start with the terrestrial welding process which possesses the best overall combination of properties required for in-space welding. [1]

Gas Tungsten Arc Welding (GTAW), better known as Tungsten Inert Gas (TIG) welding, has been selected by RI as the welding process to best fulfill the requirements of a space-based welding system. When GTAW is compared with its best adversary, Electron Beam Welding (EBW), GTAW proves to have superior potential in manual operations and adaptability to joint mismatch problems. Draw backs for EBW also include the need to shield the astronaut from additional X-ray radiation inherent to the process, and the need for a vacuum which becomes impractical for welding inside pressurized life supported compartments. Furthermore, only the energy requirements of a GTAW system can be easily met by a rechargeable and relatively small battery-pack. Such versatility would be critical in repair at locations remote from a power source, or during power-down emergency scenarios (i.e. on a space station). However, it is obvious that the terrestrial GTAW process requires some modifications (specifically in the area of vacuum operation) in order to function effectively as a space-based welding system. [1]

MICROGRAVITY EFFECTS

A mass orbiting around the Earth is continually free falling about the Earth; because, the centrifugal pull on the mass is equal in magnitude but opposite in direction to the Earth's gravitational pull. Therefore, in a space station's reference frame, the environment does not have a gravitational acceleration field. Hence, any mass element sharing the space station's reference frame, such as a molten weld puddle, has no gravitational forces acting upon it; unless of course artificial gravity is introduced via some form of acceleration. But for all practical purposes, future space-based welding applications would most likely experience low or no gravitational forces. Hence, we should question what are the effects due to the absence of gravitational forces on weld puddle formation, solidification, and joint strength. Theories to this matter are various and even conflicting, leaving much doubt as to the actual affect of microgravity on welding. If we are indeed to extend the inherent advantages of Earth-based welding out to space, it is essential to first experiment and compare the properties of a terrestrial welded joint with those of its space counterpart.

- **Development of a Get Away Special Payload (G-169)**

In 1985 RI Science Center Division began subcontracting the California Polytechnic State University in San Luis Obispo and ST International (welding systems company) to develop a Get Away Special (GAS) payload which would perform welding while on a Space Shuttle mission. NASA designated this payload as G-169 (see figure-1).

Objective -- The objective of G-169 is to allow comparison of an in-space GTAW joint to a terrestrial GTAW joint with all welding parameters held constant except for gravitational forces; welding in a vacuum is not attempted with this experiment. Upon retrieval of G-169 from its mission, the in-space (zerogravity) welded specimen would be compared to its terrestrial counterpart by RI Science Center via metallographic examinations such as macro- and micro- photography, microhardness, tensile, radiography, and scanning electron microscopy. [2]

Specimen -- One of the most attractive candidates for space-based welding application would be tubing, which may be used for structural truss elements and fluid lines. RI's Rocketdyne Division has designed Space Station Freedom's power system. The power system involves stainless steel tubing for flowing heat transfer fluids through a two-phase ammonia cooling system. Mechanical connectors which are unavoidably bulky, heavy and expensive will be used at the plumbing joints due to technology constraints. However, as learned from the Skylab Space Station, future plumbing systems should employ autogeneously welded plumbing joints, which add no mass to the joints with superbly low profile weld-beads (material at the ends of the adjacent tube sections is fused together). Such joints would be more reliable, longer lasting and dramatically cheaper. Therefore, in order to maintain a direct application for the specimen to be welded, G-169 performs a bead-on-tube (simulating a butt-joint) weld around the perimeter of an 8.9 cm (3.5 in) long X 5.1 cm (2.0 in) diameter X 1.59 mm (0.0625 in) thick wall Stainless Steel 316-L tube section; an actual butt-joint would require two adjacent sections of tube which may vibrate and separate during shuttle launch. [2]

Concept -- The basic components of G-169 include a controller, battery pack, power inverter, welding computer, welding head, and an argon gas pressure vessel. The controller manipulates and safeguards operations of the payload components. The battery pack supplies power to the entire payload via the controller. The power inverter converts the DC power-output from the battery pack to a compatible AC power-input for the welding system. The welding computer regulates power to, and operations of the welding head and argon gas purge. The welding head, housing a rotating tungsten electrode, welds along the outside circumference of the tube specimen. Lastly, the pressure vessel floods the welding zone with argon in order to imitate the gas' presence in terrestrial GTAW. Prior to launch the G-169 payload is pressurized with nitrogen gas to one atmosphere of pressure, simulating the terrestrial environment. [2]

Operation -- The sequence of operations on G-169 is regulated by a cooperation of the controller and the welding computer. Placing switch (A) of the Astronaut Payload Controller (APC) in the "HOT" position initiates start-up of G-169's (internal) controller. The controller initiates a 30 minute time delay to permit cessation of astronaut activity; scheduling activation of switch (A) within 30 minutes of crew's next sleep period should provide minimal crew induced accelerations on the Orbiter. Following this first delay, power is applied to the welding computer through the power inverter. The computer initiates an additional 7 minute time delay to permit some of its sensitive circuitry to warm up to optimal operating temperature. Following this second time delay welding is performed. The welding procedure involves 30 and 20 second periods of argon gas-flooding of the weld zone, prior and after (respectively) actual welding takes place. The actual welding (arc transfer) takes approximately 2 minutes, during which argon gas-flooding continues and the tungsten electrode rotates around the stationary tube specimen in a programmed manner. Upon completion of the welding procedure, the welding computer signals the controller to cut-off all payload power immediately. The duration for the entire experiment, including time delays, is 40 minutes. [2]

- **G-169 Flight Aboard NASA KC-135 Microgravity Simulator**

Following the Challenger Space Shuttle Accident, which prompted changes to the GAS program's safety policies and reduced space flight opportunity, RI began seeking other quicker means for microgravity simulation. Consequently, in 1990, G-169 was successfully flown on the NASA Marshall Space Flight Center (MSFC) KC-135 Aircraft Microgravity Simulation Facility.

Microgravity environment -- A microgravity environment is attainable for approximately 20 seconds by flying the aircraft through a parabolic climb and dive trajectory. G-169 produced one control specimen welded at 1g (denoted C1) prior to the KC-135 flights, three microgravity welded specimens (denoted M1, M2 & M3, chronologically), and after the KC-135 flights a second control specimen welded at 1g (denoted C2). For the microgravity welds, the operator manually started the payload's welding system just as the microgravity portion of the flight trajectory was reached, and manually stopped it as the microgravity portion was exited. This resulted in a weld of approximately 1.3 inch length along the 6.3 inch circumference of the tube. A strip chart recording of the three components of the effective gravity acceleration during each of the welds was provided by NASA MSFC. The major acceleration component for each of the three welds was as follows: M1 -- (0.05 ± 0.01)g, M2 -- (0.04 ± 0.02)g and M3 -- (0.08 ± 0.06)g. The acceleration trace was comparatively smooth during welds M1 and M2. During the M3 weld, however, the acceleration oscillated for four cycles about the average value, which was in itself approximately twice the acceleration level seen by M1 or M2. [3]

Analysis of G-169's specimens -- A visual comparison of the microgravity welds with the 1g control welds indicates no significant differences. Strip specimens were cut perpendicularly across each weld, taking care to select the central region of the microgravity welds. Metallographic examination reveal that the microgravity welds are microstructurally similar to the control welds, except for the sample from specimen M3 which shows an anomalous solidification pattern. Hardness indentations in the fusion zone and tensile tests were performed to compare mechanical properties and to attempt to quantify the cause of the unusual microstructure seen with specimen M3. Hardness values are the same for C1, C2, M1 and M2. But, for M3 the hardness is measurably greater. Room temperature tensile tests were performed on all samples to determine elongation, yield strength, and ultimate strength. The results (shown in figure-1) indicate essentially no difference in flow behavior or strength parameters. Fractography results were also comparable for both the control and microgravity samples. Although metallographic evidence and hardness results suggest a difference in weld M3, the important mechanical properties of M3 are still comparable to the control specimens'. One plausible explanation, for the metallographic and hardness differences, is that the relatively large fluctuation in acceleration during weld M3 caused some sort of "stirring effect" in the molten weld puddle which, in turn, influenced the microstructure during consolidation and hence the hardness. In summary, the significant conclusion to be drawn from these results is that GTAW in a microgravity environment should be able to produce satisfactory joints with mechanical properties comparable to those of terrestrial welds. If payload G-169 is ultimately flown on the shuttle, complete circumferential welds would be made in a more uniform microgravity environment and, thus, provide a more solid basis for the above conclusion. [3]

- **High Temperature Containerless Aircraft Furnace**

RI Rocketdyne Division, in cooperation with NASA MSFC, has modified and integrated a welding system into the NASA MSFC KC-135 Aircraft Microgravity Simulation Facility. The hardware comprising this microgravity welding system is known as the High Temperature Containerless Aircraft Furnace (HiTCAF). HiTCAF has been used to generate additional metallurgical data on melting and resolidifying of metal under the effects of microgravity. HiTCAF has also been used to demonstrate the feasibility of performing manned in-place tube welding and manual welding operations in microgravity. These NASA MSFC / RI Rocketdyne experiments mark the first time that American researchers have attempted manual welding tasks in microgravity and the first attempt by researchers of any nationality to perform manual arc welding tests in microgravity. The overall results of this research show that the GTAW molten weld pool, in microgravity, is "well behaved" with no tendency for metal expulsion or spatter, that the resulting joints' mechanical properties are comparable to those of 1-g joints, and that high quality manual welds can be performed in a microgravity shirtsleeve environment. [4]

VACUUM EFFECTS

The GTAW process requires a gas plasma, which serves as a medium for proper arc transfer between the electrode and work piece. This plasma is supplied on Earth by an inert gas (argon or helium) purge of the welding zone. Argon and helium also serve as shielding gases, which prevent the molten metal from reacting with the oxygen and nitrogen present in the terrestrial atmosphere. Obviously protection from oxidation and nitrogen poisoning is not required in the vacuum of space. However, the necessity for welding-arc transfer still remains. Due to the hard vacuum of space, conventional (as in terrestrial GTAW) introduction of an inert gas about the welding zone is impractical. Based on RI Rocketdyne experiments, the gas introduced conventionally into the vacuum is immediately dispersed in all directions, away from the gap between the electrode and workpiece. Consequently, ionization and arc establishment across the electrode gap is not achieved, and welding does not take place. (The arc can be forced to jump across the electrode gap with an increased voltage potential; however, the arc established in this manner is unstable and consequently unusable for quality welding.) Hence, a new method for plasma maintenance at the electrode gap is required to enable GTAW in the vacuum of space. [5]

- **Development of a Vacuum Arc Welding Patent**

Through IR&D, RI Rocketdyne has patented a method which allows maintenance of a stable and controllable GTAW arc in a vacuum. This method employs hollow tungsten electrode technology (see figure-2). The ionization gas (argon) is pumped through the hollow electrode at volume flow rates of less than 28 liters per hour (0.25 cf/h). This small flow rate is introduced at the tip of the electrode, where arc establishment is required. The arcing occurs primarily from the inside of the electrode hole, which superheats the ionization gas. This superheating combined with the pressure differential provided by the vacuum, accelerates the ionization gas to high enough velocities which overcome the vacuum's scattering force at the electrode gap. Moreover, the resulting welding arc is more constricted, yielding a more efficient and concentrated energy transfer to the work piece. Hence, deeper penetration welds, which are advantageous for thick structural joints, are achievable. Furthermore, when 28 l/h (0.25 cf/h) for the hollow tungsten process (used for arc ionization only) is compared to as much as 2,800 l/h (25 cf/h) with the terrestrial process (used also for shielding), the GTAW process consumables are reduced by 99% for vacuum welding. Hence the traditional draw back associated with GTAW, of expensive consumable transport into Earth's orbit, is eliminated. [1, 4, 5]

- **Reducing Hollow Tungsten Electrode Erosion**

A conventional nonconsumable tungsten electrode, which has been bored through its longitudinal axis with a small hole for plasma gas delivery, suffers from significant erosion when used in a vacuum. RI Rocketdyne, in cooperation with NASA MSFC, has managed to further develop the hollow tungsten electrode technology and reduce erosion to negligible levels. As a result, the hollow tungsten electrode has been modified into a hollow cylindrical ionization gas pressure chamber (shown in figure-2). The interior of the chamber provides a large surface area for the emission of electrons which form the welding arc. The flow of inert pressurized gas through this chamber inhibits vaporization of the hot electrode material. The outer end of the chamber forms an electrode disk which has a small orifice to release the inert gas and the arc. The electrode is held in a nonconductive cup, which confines the origin of the arc to the orifice; this prevents extraneous corona discharge to other spots on the outside of the welding torch. These features combine to reduce vacuum electrode erosion to acceptable levels. [6]

INTRA- / EXTRA- VEHICULAR ACTIVITY EFFECTS

In-space operations involve both intravehicular and extravehicular activities. Intravehicular activity (IVA) consists of operations which are performed inside the pressurized, thermally regulated, shirtsleeve environment of a space vehicle or station. The IVA environment only includes the effects of microgravity on the process and operator. On the other hand, extravehicular activity (EVA) consists of operations which are performed in the outside environment. This environment is much more challenging since it includes not only microgravity constraints, but also vacuum, temperature, and radiation effects on the process and operator. EVA effects on the operator become significant due to the constraining life support systems. Therefore, robotic, teleoperated, and semi-automated systems may come into play for specific types of EVA welding operations. [7]

- **IVA Simulation**

Using the KC-135 Aircraft Microgravity Simulation Facility, RI Rocketdyne, in cooperation with NASA MSFC, has performed unprecedented manned orbital tube arc welding and manual arc welding experiments in microgravity, with results which are directly applicable to IVA operations (see above HiTCAF discussion under "microgravity effects") . The experiments' objectives were to achieve preliminary workload and dexterity studies for both semi-automated orbital tube welding and manual welding in the shirtsleeve IVA environment. The results were successful and showed no problems, due to a microgravity environment, in producing high quality GTAW joints. [4]

- **EVA Simulation**

RI Rocketdyne, in cooperation with NASA MSFC, contracted McDonnell Douglas Astronautics Company to simulate an EVA involving manual operations with a semi-automated orbital tube welding device. This evaluation was performed on McDonnell Douglas space station fluid line models, in their neutral buoyancy water tank facility, with a fully pressure-suited test subject. The results reaffirmed certain welding hardware design considerations for interfacing with the astronaut, and established time-line estimates for fluid line assembly by welding. No fundamental problems were evident with performing an EVA to support in-space semi-automated orbital tube welding operations. [4]

- **Design of an EVA Welding Experiment**

Funded by NASA's In-Space Technology Experiments Program over a twelve month period between 1988 and '89, RI Rocketdyne and the California Polytechnic State University of San Luis Obispo developed a detailed understanding, and designed a four hour Space Shuttle EVA welding experiment. The experiment design consists of both manual arc welding and semi-automated orbital tube arc welding tasks to be performed at a dedicated workstation mounted to the cargo bay sidewall of the Space Shuttle. The experiment is designed to provide the data necessary to complete development of a fully functional, highly flexible, in-space, EVA welding capability for assembly and repair of space based structures. Safety analyses, performed by NASA JSC Safety Division and Astronaut Office, found no prohibitive issues with the experiment design. However at this time, due to lack of funding, the experiment remains on RI's drawing board. [4, 8]

- **Development of Enhancement Technologies**

RI has and continues to develop a variety of technologies which should enhance in-space welding operations, especially for EVA. These technologies are primarily in the following areas: robotic, teleoperated, semi-automated and manual welding; real-time weld quality analysis and parameter control; hollow electrode filler wire feeding; and rechargeable battery powered welding.

<u>Welding torch vision and data collection system</u> -- RI Rocketdyne, in cooperation with NASA MSFC, has developed, employed and refined various welding torch vision systems for both open loop and closed loop operations. With advancing technology in video camera, fiber optic, lense, filtration, and electronic systems, effective real-time weld monitoring and control have been tremendously improved for remote and robotic welding operations. Viewing, through the welding torch, the magnified welding process' interaction with the workpiece, provides excellent feedback for real-time control, weld quality evaluation, and weld parameter development. A computer can also gather data from sensors while a video camera observes the weld in progress. The computer sends the data to a vision processor, which superimposes the data on the image from the camera. The operator, thus, can watch the weld bead simultaneously with the instantaneous values of such data as elapsed time, welding current, and processed sensor measurements of the weld area, such as weld back-bead width and depth of penetration, pool temperature, or top bead dimensions. The video image and superimposed data can be recorded on magnetic video tape. Consequently, the welding operation can later be reviewed in slow motion or even frame by frame. The pertinent data is always instantly available to the viewer and correlated in time with the image of the weld. In summary, implementing a welding torch vision system with a computer data collection and display system

may be critical for achieving successful in-space robotic, teleoperated, semi-automated, and even EVA manual welding operations. [9, 10, 11]

Welding with infrared thermography -- A high-resolution infrared imaging and image-data-processing system has been implemented as a thermography tool by RI Rocketdyne, in order to control welding parameters and to ensure reliable joints. The system displays a real-time image of the weld in which temperature gradients are characterized by colors. Consequently, welding defects, such as impurities, gaps, surface irregularities, porosity, and tungsten inclusions are evident from the thermographical signatures they produce. Furthermore, the system extracts data from the thermography image. This data may be processed to determine the degree of weld penetration and the effects of back-side cooling. Such a system combined with the welding torch vision and data collection system, described above, can become an effective real-time weld control and inspection tool for in-space robotic, teleoperated, semi-automated, and even manual welding operations . Employing such systems may also be valuable in developing proper in-space welding techniques and parameters, by building a data base from in-space welding experimentation. Lastly, infrared thermography of an EVA manual welding operation may become a critical monitoring and control tool for astronaut safety. [12]

Robotic welding with artificial intelligence -- For years, RI Rocketdyne has been developing robotic welding techniques for improving reliability, consistency, and efficiency of welded joints in rocket and space shuttle main engine manufacturing. Rocketdyne's efforts have been fruitful with many non-precedented achievements in robotic welding. These achievements are primarily based on artificial intelligence tools designed into robotic welding systems. The artificial intelligence tools, which have been implemented to various degrees in Rocketdyne's manufacturing lines, provide real-time automated monitoring and control capabilities of the welding process, such as weld seam tracking, weld penetration, bead height, welding current, arc voltage, wire feed rate, and travel speed. Using such technology seems imperative for the in-space environment, where manual monitoring and control are limited, and first-try acceptable quality welds are essential.

Filler wire feeding through tungsten electrode -- Filler wire feeding is necessary for welding thick joint members, gap bridging, and element reconstruction or repair. The hollow tungsten electrode technology opens new possibilities with filler wire feeding. Feeding the filler wire through the hollow electrode has been successfully applied by RI Rocketdyne in the terrestrial environment. A variety of advantages to welding in such a manner may be applicable to IVA and/or EVA in-space operations: Wire feeding is preheated and, therefore, can be fed at high speeds without spattering. High-frequency energy does not have to be supplied to the workpiece to initiate welding. The size of the arc gap is not critical; a power-supply circuit can adjust the voltage across the gap to compensate for changes. Only a low gas flow rate is needed. The welding electrode can be replaced easily as a prefabricated assembly. An external wire-feeding manipulator is not needed. Lastly, the welding process becomes more forgiving of operator error, and more tolerant of non-linear joints. [13, 14]

Rechargeable battery powered welding -- Development of G-169 as a GAS payload, required that the GAS canister contain the experiment's power source. This constraint drove RI Science Center's successful development of a welding system which is powered by a rechargeable battery pack. This technology achievement proves that in-space welding operations do not have to interfere with spacecraft power constraints, and are feasible with a rechargeable back-pack power supply at remote sites or during power-down contingencies. Battery pack performance with the GTAW process has a great potential for improvement using today's continuing technology advancements. [2, 7]

SPINOFF TECHNOLOGIES

Incorporation of the hollow tungsten electrode technology with the GTAW process, reveals spinoff applications for both in-space and terrestrial operations. Some of the in-space spinoff applications may become as important as welding and, therefore, may drive the design of an in-space welding system to also serve as an in-space surface treatment system, cutting torch system, and possibly a metal removal system.

- **Vapor Deposition of Metal**

A vacuum gas-tungsten-arc vapor-deposition process has been developed by NASA MSFC and RI Rocketdyne as a result of the hollow tungsten electrode technology breakthrough. The process yields highly reflective, smooth metallic films that reproduce almost perfectly the contours of the surfaces on which they are deposited. The rate of deposition can be controlled precisely, and the surface texture can be varied, if desired. The process is capable of deposition at rates double those of standard sputtering. This process may be applied in the making of thin metallic coatings, which can serve as electrical conductors, radio reflectors or antenna elements, and optical mirrors of partial or ultrahigh reflectivity. The potential for this surface treatment process to lend itself to in-space operations, such as refurbishing and repair of coated spacecraft elements which have been eroded by atomic oxygen bombardment, is compelling. [15]

- **Key Hole Cutting**

The vacuum GTAW system's use of a high velocity gas which transfers an arc from the hollow electrode tip to the workpiece is suited not only for welding, but for cutting as well. With a slight increase of the ionization gas's volume flow rate through the electrode, the consequent increase in the welding arc's pressure can penetrate the material thickness and produce key hole cutting. This spinoff has been experimentally demonstrated by RI Rocketdyne. This "extra feature" serves as a significant advantage for the space modified GTAW system; because it allows conversion (with a turn of a knob) of the welding mode into a cutting-torch mode. [5, 8]

- **Metal Removal**

In-space metal removal is a critical technology needed for fit-up problems and repair. Machining by grinding and chipless cutting creates debris and causes diffusion bonding. However, an improved technique has been proposed for metal removal using the hollow tungsten electrode technology. The metal to be removed would be melted with a welding arc from a hollow tungsten electrode, and then drawn off with a second hollow electrode. This approach would depend not on gravity to siphon or atmospheric pressure for force, but rather on microgravity capillary attraction which should pull the molten metal through the tube. Should such a process become workable, the benefits to be gained are enormous. [16]

FURTHER R&D REQUIRED

RI has come a long way in bringing about in-space arc welding technologies through both internal and NASA funded R&D efforts. However, the capability to perform construction and repair of metal structures in space, by welding, is still unavailable. Certain R&D must further take place in order to produce an effective in-space welding system, which may be applied by programs such as Space Station Freedom, Lunar Base, and Manned Mission to Mars. This further R&D should be based on experimentation using KC-135 microgravity simulation, Space Shuttle small autonomous payloads, and Space Shuttle IVA and EVA (see figure-4).

KC-135 SIMULATION FACILITY EXPERIMENTS

RI Rocketdyne has proposed, to NASA, the integration of a welding vacuum chamber into the KC-135 Microgravity Simulation Facility. Should such integration be accomplished, NASA MSFC's KC-135 will serve as a combined microgravity and <u>vacuum</u> simulation facility.

- **Hollow Tungsten Electrode Welding In Microgravity-Vacuum**

A KC-135 microgravity-vacuum simulation facility would enable first time testing of the vacuum modified GTAW process in microgravity, an essential step towards in-space arc welding capability. RI expects that further refinement of the potential in-space arc welding process would be accomplished, especially in controlling the interaction of arc force, ionization gas flow, and surface tension in the microgravity-vacuum. In addition, behavior of non-autogenous in-space arc welding, using filler wire feeding systems which lend themselves to both automated and manual operations, should be examined and refined in the simulated microgravity-vacuum environment.

- **Microgravity-Vacuum Orbital Tube Welding System**

Due to the attractive in-space applications for a semi-automated orbital tube welding system (see earlier discussion of G-169 specimen selection), it is desirable to extend the vacuum modification of the GTAW process to the orbital tube welding device. Such modifications are not as straight forward as those for a conventional GTAW torch, because the orbital tube welder consists of an electrode which is driven around the tube circumference by an orbiting gear system. The mechanical and fluid challenges, of integrating a hollow tungsten electrode and ionization gas delivery system into an orbital welding head, are considerably more complex. However, use of the KC-135 should assist in such development and testing of an in-space tube arc welding system. [8]

- **Spinoff Technologies in Microgravity-Vacuum**

Finally, RI should utilize the KC-135 simulation facility to expand on the spinoff technologies made available by the in-space arc welding process. These technologies, which include vapor deposition of metal, key hole cutting and metal removal, require further development and testing in the microgravity-vacuum environment. The KC-135 should help determine whether one versatile in-space metal processing system can be developed to perform a number of tasks including welding, surface treating, cutting, and metal removal.

SPACE SHUTTLE SMALL PAYLOAD EXPERIMENTS

KC-135 simulation of a microgravity-vacuum environment should be effective for most R&D and some testing of in-space metal processing techniques such as welding. However the KC-135 is only a simulation facility, and not the real thing. At some point along the development path of in-space welding or any other metal processing technique, we should experiment and demonstrate the process in the actual space environment. Using NASA's Shuttle Small Payload Programs, such as the Get Away Special (GAS), Complex Autonomous Payload (CAP) or Hitchhiker (HH), excellent experiment and demonstration platforms may be achieved with cost effective results.

- **G-169's Current Situation**

G-169, in its present (almost flight ready) configuration, is suffering from a variety of weaknesses, which include: overweight, outdated technology, marginal reliability, limited experiment value and lack of funding.

<u>Overweight</u> -- G-169 employs a single full size GAS canister with a 90.7 kgf (200 lb) weight limitation on the canister's contents. In 1990, the flight ready G-169 payload weighed in at 96.6 kgf (213 lb); 5.9 kgf (13 lb) over the limit. The payload was originally designed to weigh in at 86 kgf (190 lb) with an extremely dense and efficient package design. However, due to growing package integration complexity and NASA's post-Challenger shift to more conservative design requirements, G-169 gained weight mainly from battery box development and added structural supports. The 5.9 kgf (13 lb) cannot be trimmed from the payload without major redesign and development, and the 90.7 kgf (200 lb) limit cannot be waived due to strict GAS program guidelines.

<u>Outdated technology</u> -- G-169's welding system employs a modified ST International NIKA Power 100 (model 9101) computer driven, solid state, transistorized, welding power supply. This unit was developed in the early 1980's. With almost everyday advancements in electronics from the 1980's into the 90's, G-169's welding system has become an antique. The welding system is very difficult and expensive to maintain since many of its components are no longer readily available. In fact, G-169 has reached a point, where the welding manufacturer can no longer maintain the outdated system without rebuilding and upgrading it to todays technology level.

<u>Marginal reliability</u> -- Due to G-169's single, full size, canister volume limitation of 141.6 liters (5 cu-ft), no redundancy could be built into any of its systems. One canister provides just barely enough volume and weight capacities for a basic welding experiment. For example, should welding arc strike fail (a common phenomenon), the arc strike is automatically re-attempted a couple of times, but with the same electrode; usually arc strike fails due to a problem with the electrode itself. At least two welding heads, with one specimen each, would provide much greater odds for experiment success, and most likely additional data. Further more, G-169's extensive battery-pack has ample capacity margin for welding in room conditions with a fully charged bank (4 times). However, welding at a typical 0°C environment after 3 unattended months reduces the battery capacity by almost 50% (assuming batteries are in ideal condition), leaving only twice the required capacity. Such an experiment should realistically have a

higher capacity margin to ensure good results. In addition, the shielding inert gas supply system could use some redundancy in its design to ensure best welding results. Lastly, the welding system's numerous electronic components are marginally reliable when faced with a harsh vibration environment. Many of the components are potted, but not all. A shake table test of the payload (after its KC-135 flights) caused some breakage in the welding system's electronics.

Limited experiment value -- G-169's three successful runs aboard NASA's KC-135 Microgravity Simulation Facility and additional microgravity welding investigations using HiTCAF have yielded some good factual data, showing that microgravity effects on the welded joint's mechanical properties are negligible. Additional data, especially from a zerogravity environment, would be beneficial but not crucial. The "green light" for progressing further towards microgravity-vacuum welding experiments has already been given by the KC-135 results. Hence, flight of G-169's current configuration aboard the Space Shuttle, with its marginal reliability, no longer justifies the cost of preparing its welding system for flight.

Lack of funding -- With todays troubled economy and tight aerospace budgets, it has become unrealistic to fund G-169's final preparation for flight aboard the Space Shuttle. G-169's current configuration does not warrant any further expenditure of RI IR&D funds. The only hope remaining for G-169 is its reconfiguration, as part of a large NASA R&D contract for a series of strategic welding experiments leading to eventual development of an in-space welding system.

- **Lessons to Be Learned from G-169**

G-169's current configuration should be viewed as a prototype which has provided rich hands-on experience to university students, three microgravity welded specimens, a battery powered welding system, and numerous lessons to be applied on future similar payload systems. Each of G-169's phases of "life", including payload design, development, integration, testing, safety approval process and KC-135 flights, teaches some valuable lessons for future endeavors.

Payload design, development, and integration -- Before spending time, excitement, and effort on the payload package design, one should take the time to research and understand all the NASA requirements which the design must satisfy. The designer should understand the fault tolerances required by safety for each of the various systems. A layout of all the requirements on the drawing board is advisable. For example, if one overlooks that two pressure relief valves rather than one are required in the plumbing system, once the payload is completed NASA may catch it in a final inspection, even though they should have caught it in the early design stage. A complete design job up-front will save significant time, money, and frustration down the line; it may even make the difference between success or failure. A 3D CAD system can allow complete construction and development of the payload on "paper" without making any commitments. Such detailed development up-front should also allow accurate determination of expected payload weight. Exact weight determination, after the payload is fully built, may be too late.

When designing the payload's support structure, one should keep in mind that structural strength under compression and tension is important, but does not guarantee structural rigidity. The payload structure should be sufficiently rigid so as not to sag in a launch configuration. Moreover, the support structure should be designed to accommodate some location shifting of payload components during integration.

Employing a modular approach to the design of the payload systems may add extra weight and use more volume, but modularity provides tremendous benefits and possibilities throughout payload development, integration, testing, trouble shooting, and repair. Modular systems should be removable from the payload by simple disconnection of structural supports and single input and/or output power, control and/or fluid lines. Use of commercially available, off-the-shelf components lends itself well to a modular design approach. Components, such as a welding system that employs complex electronics, may require regular maintenance and repair. These type of components should not be reconstructed on a payload's structural shelf. Rather, their inherent off-the-shelf modularity and design should be maintained to allow easy servicing by the manufacturer. Furthermore, systems with electronics may become outdated and unserviceable within the payload's active life-span. Therefore, modularity allows relatively easy system replacement or upgrade.

Design of the payload's rechargeable battery power supply, should make provisions to allow for easy switching from payload autonomous power to bench supply power. Reliable bench supply power, simulating the battery pack, is important for payload systems development, integration, and checkout.

Payload testing -- During payload testing, which may occur throughout development, any use of rechargeable batteries should be carefully documented. Detail of battery performance (potential, current, power) before, during, and after each use, and in between charging periods should be recorded. One should construct a detailed history of the batteries' performance to determine proper care (through proper charging and discharging), and to determine reliability for the eventual flight. Furthermore, testing the battery pack's performance at 0°C, after a three month shelf period at room temperature, may be necessary to ensure payload performance during flight.

Vibration testing of the payload's structure, should be set apart from vibration testing of the remaining payload systems. The payload structure should be rugged enough to handle any of the NASA suggested vibration tests, which usually depict Space Shuttle crash landing loads. However, non-structural payload systems do not need to be subjected to vibration intended for structural testing. It is not important whether the payload can run its experiment after a crash landing of the Shuttle. But, it is critical that the payload wont structurally fail and propagate additional damage to the Shuttle in a worst case scenario. Therefore, one should use common sense and realistic launch vibration tests for the payload's electronics, mechanisms, and other sensitive non-structural components; otherwise, such components may break needlessly and set back schedules.

Should any special testing of the payload or its systems be required, such as a battery box or plumbing system proof pressure tests or an EMI test, make certain that NASA provides exact testing requirements (in writing). The standard provided literature, such as safety manuals or experimenter handbooks, may not have reliable or sufficiently detailed requirements. It can become very frustrating and costly when the safety approval process decides that some of the testing parameters or methods used are unsatisfactory.

Finally, if your testing results are marginal, it is usually easier to redesign, enhance, or fortify the system or component rather than battle the NASA safety organization for their approval.

Payload safety approval process -- For a payload with an inherently hazardous experiment, such as welding with G-169, the NASA safety approval process may become one of the toughest obstacles to cross. There appears to be some undefined requirements, inconsistent rationale, personal policies, and changing political tones which shape the progression of the safety approval process. The process itself may be clear and defined, but the safety people, who make the decisions along the process path, may be replaced by others somewhere along the way. Such situations may lead to inconsistencies. With G-169, the safety approval process began before the Challenger Accident, which drove many changes throughout Space Shuttle programs, including GAS. Consequently, G-169 experienced a roller-coaster ride; decision making people at NASA changed and so did their policies.

Early design decisions, which evolve into built products, may be reversed leading to set backs, hardships and additional incurred costs for the payload user. Be-aware, the Space Shuttle program is not a commercial airliner. The Shuttle program is still experimental and probably will always be so. The Shuttle's design lends itself to constant experimentation and uncertainties. In this day and age of un-assured access to space, the Space Shuttle is a treasure and the chance to use it is a privilege, which the payload user should not expect, even if the price to fly is paid. In order to fly a payload on the Shuttle, one must expect the unexpected in the safety approval process. Only those payload users, who are lucky or persist and have enough money to keep up with set backs, will get the chance to fly.

The payload user should try to treat the relationship with NASA, as a relationship with a contractor. The user is the paying customer. NASA is the delivering contractor. It is true that this relationship is not straight forward due to reasons mentioned above. However, by keeping tabs on all agreements reached, especially early in the design process, including record of dates, names, and exact agreement context, the payload user has a better chance of protecting the payload from set backs later down the "dark" path of the safety approval process.

When formulating hazard inhibits and safety controls, similarity analyses should be avoided. Similarity analyses are prone to personal interpretation and refutation. NASA safety may easily dismiss such analyses. Furthermore, the GAS canister should provide the payload user with some basic hazard inhibit backups, such as containment of some loosened components, pressure system failures, explosions, shrapnel, temperature extremes, and chemical spills. However, the canister's quantitative containment capabilities are not well determined or accepted by NASA as valid inhibits.

KC-135 flights -- In G-169's case, the KC-135 flight proved to be valuable. It enforced testing of the payload system in full flight configuration (with the exception of the GAS canister shell). Consequently, several software "bugs" were detected with the welding system, which were invisible to the bench tests. The software was corrected, and three successful KC-135 flights ensued. However, it was evident that a Get Away Special experiment like G-169 is not meant to efficiently utilize the capabilities of the KC-135 Microgravity Simulator. Due to turbulence or imprecise flight control, the simulated microgravity of 20 seconds per run, at times, may be "rough" (with minor induced g-loads). Thus, the KC-135 program is designed to repetitively run an experiment as often as 40 times per day, 4 days per week, for a total of approximately 160 runs per week. Only with such repetition, can large amounts of high quality microgravity data be gathered. The G-169 payload requires some disassembly for sample removal and replacement, can only sustain power for 4 consecutive experiment runs, and requires almost two full continuous minutes of microgravity for full weld completion; hence limiting the utility of the KC-135. To summarize, the KC-135 may be useful in experiment testing and debugging, and can also yield some useful microgravity data.

- **Shuttle Side-Wall Autonomous Metal Processing Payload**

RI should utilize its G-169 and G-170 Shuttle Small Payload reservations for development of a new dual-canister payload system, which may become known as the Shuttle Side-Wall Autonomous Metal Processing Payload (SSWAMPP); in hope that it should "swamp" the space program with a variety of in-space metal processing techniques. SSWAMPP should be developed to serve as a reliable, versatile, automated experiment and demonstration platform for in-space welding and other potential in-space metal processing techniques, such as metal vapor deposition, metal cutting, metal removal, and even pressure vessel metal casting [16]. SSWAMPP should be designed to support an extensive series of flight experiments, which may include the following phases:

PHASE	PAYLOAD DESIGNATION	EXPERIMENT OBJECTIVE
I	G-169 / G-170	payload system flight test with zerogravity-one atmosphere orbital tube arc welding
II	G-XXX / G-XXX+1	zerogravity-vacuum bead-on-plate arc welding
III	G-XXX+2 / G-XXX+3	zerogravity-vacuum orbital tube arc welding
IV	G-XXX+4 / G-XXX+5	zerogravity-vacuum metal vapor deposition
V	G-XXX+6 / G-XXX+7	zerogravity-vacuum key hole metal cutting
VI	G-XXX+8 / G-XXX+9	zerogravity-vacuum metal removal
VII	G-XXX+10 / G-XXX+11	zerogravity-vacuum pressure vessel metal casting

The proposed SSWAMPP design consists of two GAS canisters which are coupled via power, control, data, and fiber optic video lines. One of the canisters serves as the Power-Monitor Can, while the other is the Metal Processing Chamber Can (see figure-3).

Power-Monitor Can -- The Power-Monitor Can is designed to provide experiment power, control, and data retrieval. Elements, including a large rechargeable battery pack (with redundant capacity), a power inverter, a programmable computer controlled power supply with data storage capabilities, and an infrared thermography image processor and video recording device, are all integrated via a modular approach into one full size GAS canister. The canister is pressurized with nitrogen to terrestrial atmospheric pressure. The Power-Monitor Can is designed to retain a constant hardware configuration, while software changes are easily made, in support of a variety of metal processing experiments.

Metal Processing Chamber Can -- The Metal Processing Chamber Can houses and safely contains the automated metal process experiments. Elements, including specimens, hollow tungsten electrode devices (i.e. welding torch), ionization gas supply system, and a Freon active cooling system, are all integrated via a modular approach into one full size GAS canister. The canister can be pressurized with nitrogen to simulate the terrestrial atmosphere or left open to ambient pressure. The Metal Processing Chamber Can is designed to support data collection sensors, such as accelerometers, barometers, video cameras, and infrared fiber optic receptors. The full size GAS canister also provides sufficient space for redundancy built into the elements described above; at least two specimens are each supported by their own dedicated systems.

- **Benefits of Dual Canister Payload Approach**

After carefully examining the experiences and lessons learned from G-169, a dual canister payload approach seems to provide the needed resources for achieving an effective in-space metal processing experiment platform such as SSWAMPP.

Improved modularity -- Two canisters force a natural split of the overall payload system into two modular parts; for example, a power, control, and data collection module coupled with an experiment chamber module. The double volume and weight capacity, offered by the dual canister approach, also allows modularizing of the individual payload systems within each canister. Rather than integrating the systems into a closely packed and inter-meshed "jungle" of wires, cables, mechanisms, fluid lines and alike, with a dual canister approach one can afford to be more organized and neat. Organization of the separate systems into compact individual modules, which can be easily removed from the payload package for maintenance, repair, upgrade or even last minute replacement with a spare, may prove to be invaluable; especially if the payload system may be re-flown to support a continuing series of experiments. Modularity prevents "ripping" the entire payload package apart to fix a problem, especially during development. Modularity also lends itself to simpler bench tests and locating of problem origins. Further more, development and successful use of generic modules, such as for power, control, or data collection, may generate a commercial market for the benefit of the Shuttle Small Payload user.

Less failure propagation -- The basic modularity established by the two canisters, and any further modularity within the canisters themselves should result in a less complex and inter-meshed system. Consequently, a failure within a particular module should remain localized and not propagate into additional system failures, due to close system packing. Protection of an individual module from an adjacent module failure becomes simpler by shielding each module from electrical surges, temperature extremes, chemical spills, foreign objects, and/or debris collision.

Higher reliability -- With the double volume and weight capacity, offered by the dual canister approach, redundant systems can be more readily employed to ensure return of at least some flight results. Systems such as power, control, data collection, experiment process, and specimens can all be duplicated to some extent and set apart as independent redundant systems.

More experiment capability -- With the added volume and weight capacity available for more extensive power supply and experiment apparatus, additional specimens can be flown and experimented with. This provides not only for redundancy, but also for added variability with experiment parameters. As an example, added variability for the welding experiment may mean some variety among specimen materials, welding schedules, and/or plasma gas mixtures.

Two separate environments -- With two separate payload canisters, at least two separate environments are easily achievable. For example, the welding experiment can employ a nitrogen pressurized canister for the electronic systems, which normally are not designed to operate in a vacuum, and a non-pressurized (ambient) canister for the in-space welding process, which is to be tested in a vacuum.

IVA AND EVA EXPERIMENTS

Space Shuttle small autonomous payloads would allow us to safely experiment and contain the in-space welding process, without the involvement of human factors. However, human factors eventually have to become an integral component of maturing in-space technologies, such as welding. Consequently, both IVA and EVA experimentation would be required to demonstrate the practical application of in-space welding and any spinoff in-space metal processing technologies.

Spacelab IVA Glove-Box Experimentation

The Space Shuttle program's use of the Spacelab laboratory module is tailored for purposes such as glove-box manual or semi-automated welding experiments, simulating IVA applications. An upgraded, space qualified derivative of the KC-135 glove-box experiment set-up may be designed for integration and flight aboard Spacelab. Demonstration of arc welding, in both the manual torch and semi-automated orbital tube modes, should be attempted in a pressurized glove-box, as well as in vacuum. In addition, demonstration of spinoff technologies, such as metal vapor deposition, key hole cutting, and metal removal, should also be attempted. Spacelab experiments would allow highly controlled in-space testing of the resulting technology, developed through the KC-135 microgravity-vacuum simulation laboratory and the SSWAMPP.

Cargo Bay EVA Experimentation

The ultimate phase in experimentation, demonstration, and application of an in-space welding capability and other potential metal processing options, is taking these new construction and repair techniques outside of the spacecraft into the EVA environment. A detailed design of a Space Shuttle cargo bay experiment has already been developed (discussed above). An EVA experiment set-up would require a specialized work station and a variety of enhancement tools and safety features to support the astronaut with such new and relatively hazardous metal processing operations. Tools, such as the RI developed welding torch vision and infra-red thermography systems, may become integral safety and data collection elements of an EVA welding experiment. Combining SSWAMPP hardware, existing Hitchhiker hardware elements (such as the SPOC adapter, SPOC mounting and cooling plates, and SPOC avionics units), and existing EVA hardware (such as foot and other body restraints), is all entirely possible. Many of the resources needed to perform EVA experimentation with potential in-space metal processing technologies, such as welding, already exist.

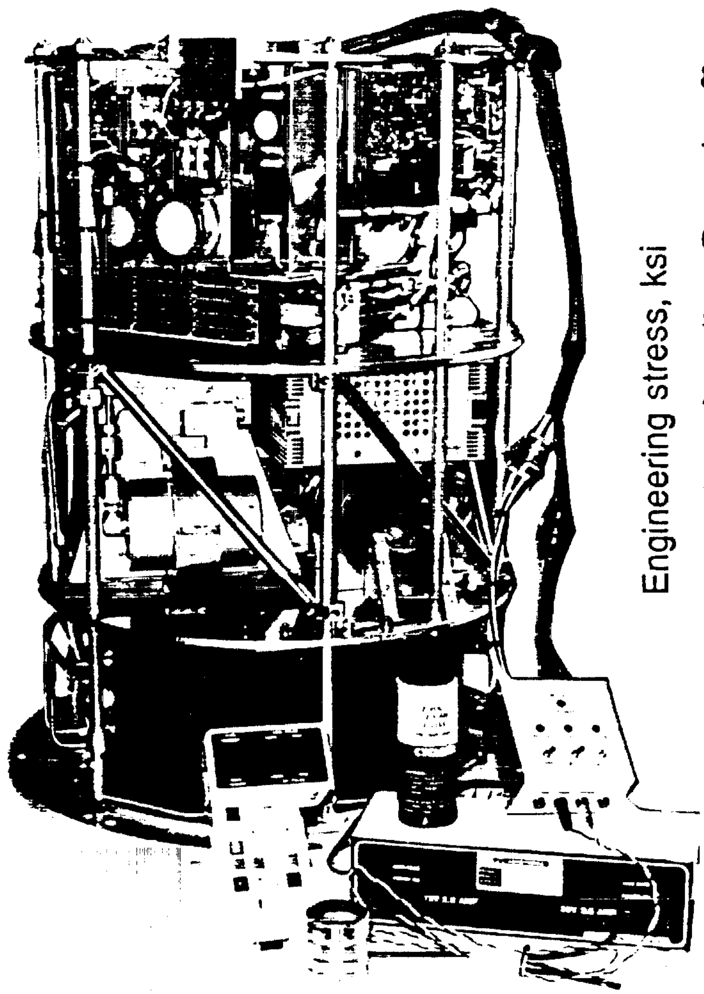
CONCLUSIONS

Welding is a hazardous and challenging operation to master. However, the benefits to be gained from welding capability are tremendous and continue to prove themselves time and time again in terrestrial production and repair of buildings, automobiles, ships, submarines, aircraft, and spacecraft. Just about any system employing metal structure, also employs welding as the joining method for that structure. There is no denying that welding is our most advanced and practical building methodology on Earth. We have even found ways to weld under water, in the oceans, where undersea settlements are already occurring. Consequently, it is only natural that we should find a way to extend this terrestrial methodology into space, as we begin to make our way into this next frontier which we are also bound to settle.

Today, in-space operations are restricted to tasks which on Earth are relatively simple to perform (excluding microgravity assisted tasks). Welding on Earth is not a simple task, and consequently in space it may become far more complex than its terrestrial counterpart. However, in-space welding can become a reality. It just takes development of appropriate technology. Of course, development of such technology requires time and money. The time will come, and money will be appropriated. In fact, the Soviet (now Russian) space program has already made the time and invested the money into a proven EVA electron beam versatile hand tool, which can weld, vapor deposit metal, and cut. Moreover, cosmonauts have already found practical applications for this tool during an EVA repair of the MIR space station. It is only prudent to conclude that NASA should at least have similar repair capability.

RECOMMENDATIONS

We are entering an era of imminent and permanent space exploration, habitation, and cultivation. The need for in-space welding and other metal processing technologies has already been clearly defined by NASA and demonstrated by the Soviet (Russian) space program. It is time for NASA to authorize its contractors, like Rockwell International, to develop the technologies required by NASA's upcoming, and already beginning, ventures. In-space welding technology is in Rockwell's reach. Rockwell International divisions, such as the Science Center, Rocketdyne, and Space Systems, should work together and complete the development of an in-space welding system with options for other in-space metal processing capabilities. NASA resources, including the KC-135 Microgravity Simulator, Space Shuttle Small Autonomous Payloads, and Space Shuttle IVA and EVA, should all be strategically employed to develop in-space metal processing capabilities, such as welding (see figure-4).



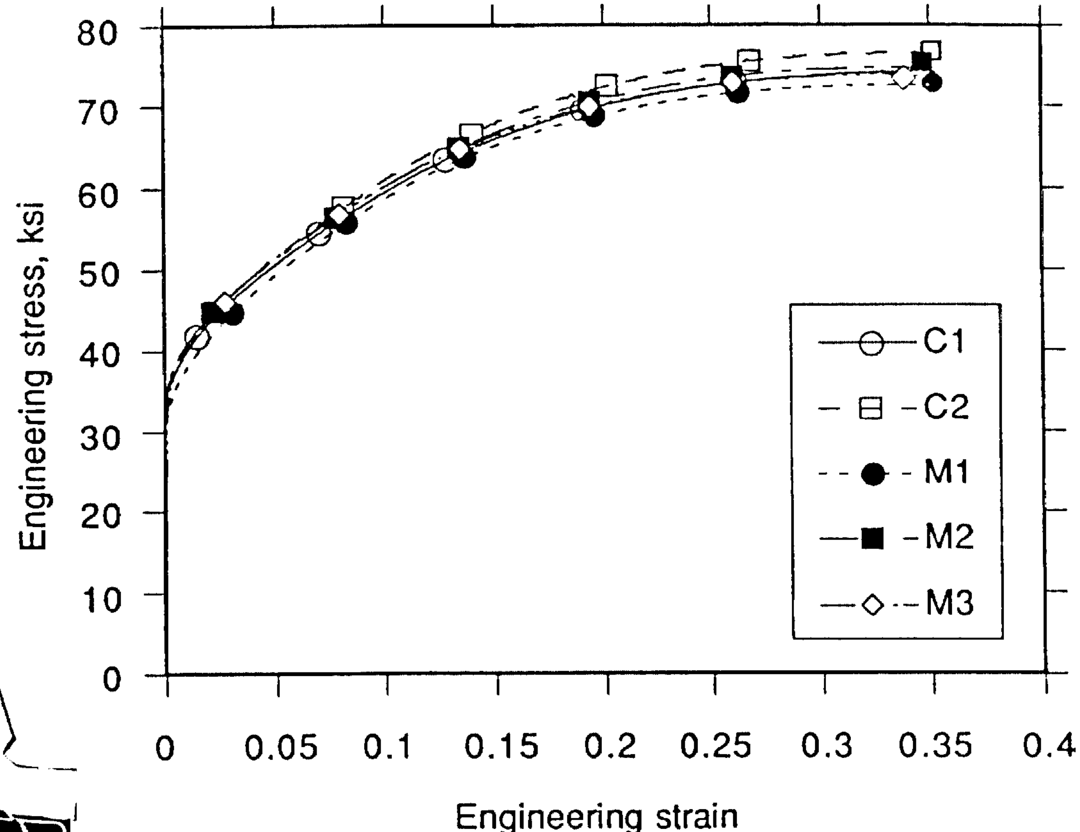
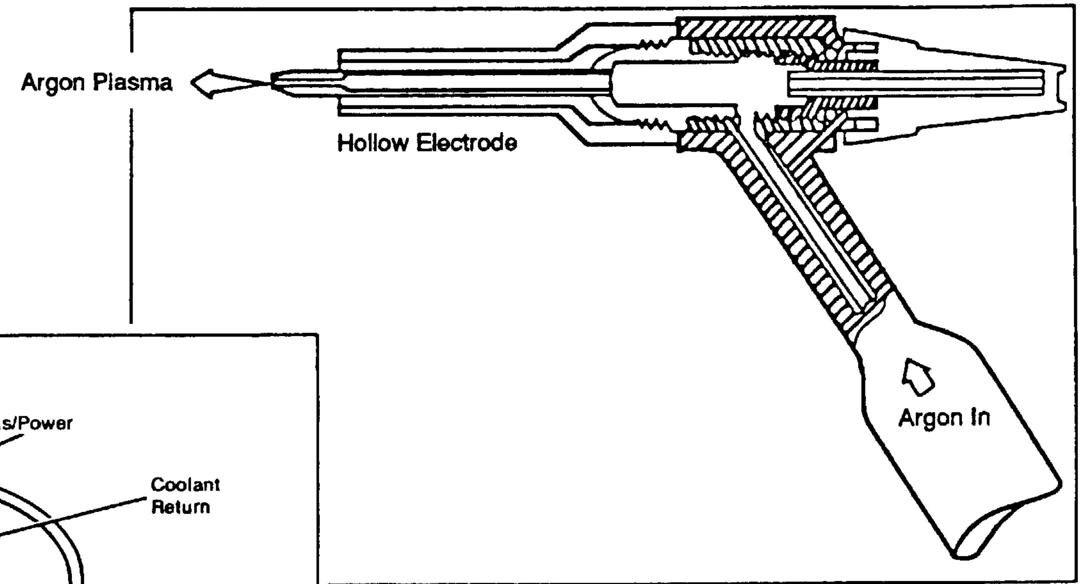


Figure-1: G-169 Get Away Special In-Space Welding Shuttle Payload with KC-135 Microgravity Flight Results.

Flow stress behavior of welded 316L stainless steel, show essentially identical properties for control samples (C1 & C2) and microgravity samples (M1, M2, & M3).
(Courtesy of Rockwell International Science Center Division IR&D)



Rocketdyne Vacuum GTAW Torch

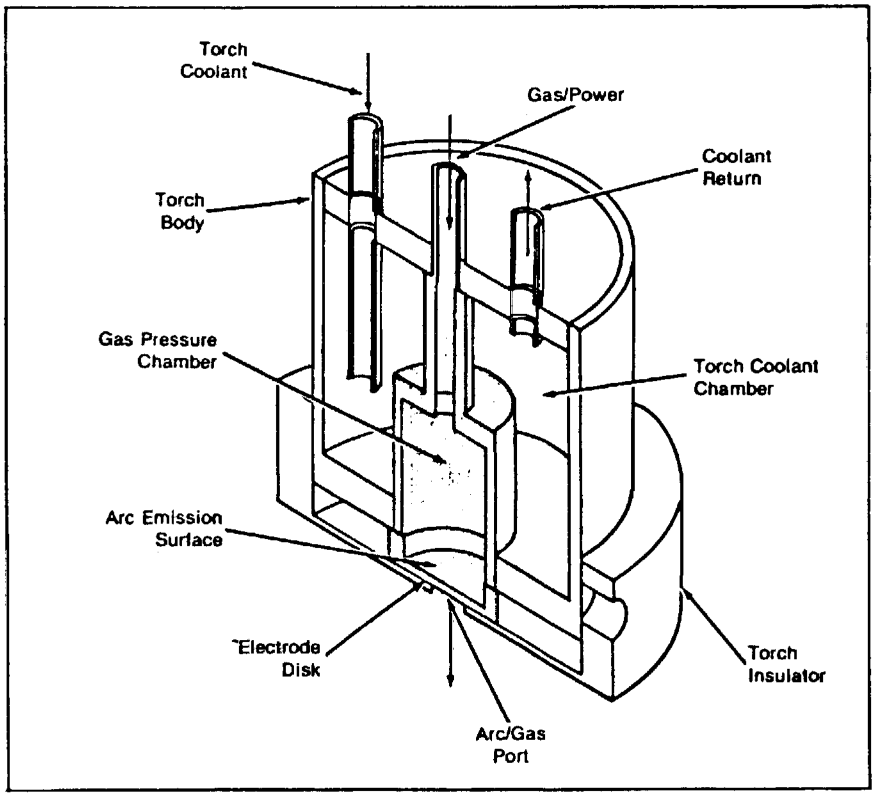


Figure-2: Hollow Tungsten Electrode Patent for Vacuum Gas Tungsten Arc Welding

(Courtesy of NASA Marshall Space Flight Center and Rockwell International Rocketdyne Division R&D)

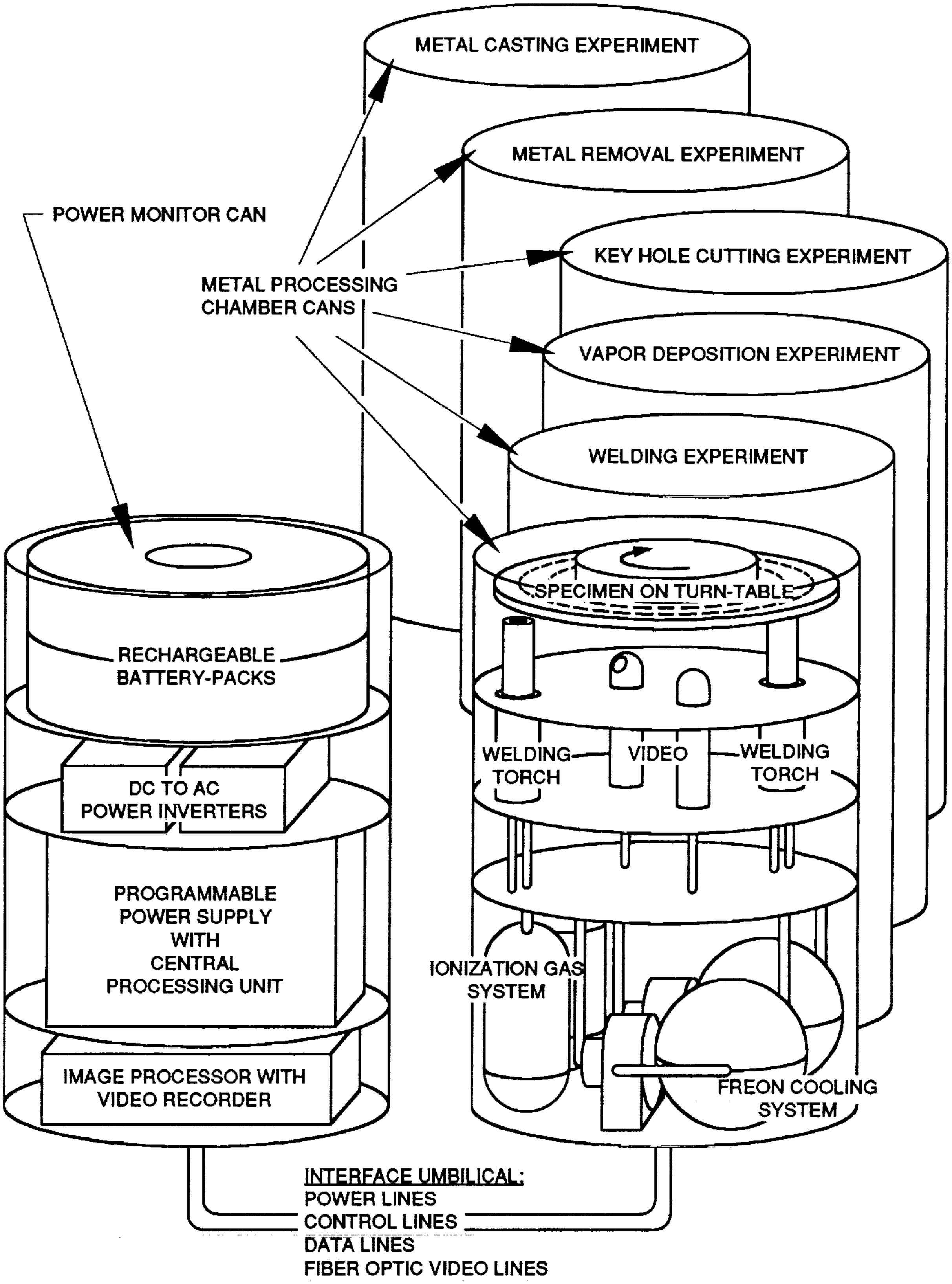


Figure-3: Shuttle Side-Wall Autonomous Metal Processing Payload (SSWAMPP) Series, Using Dual GAS Canister Approach

(Courtesy of Rockwell International Space Systems Division)

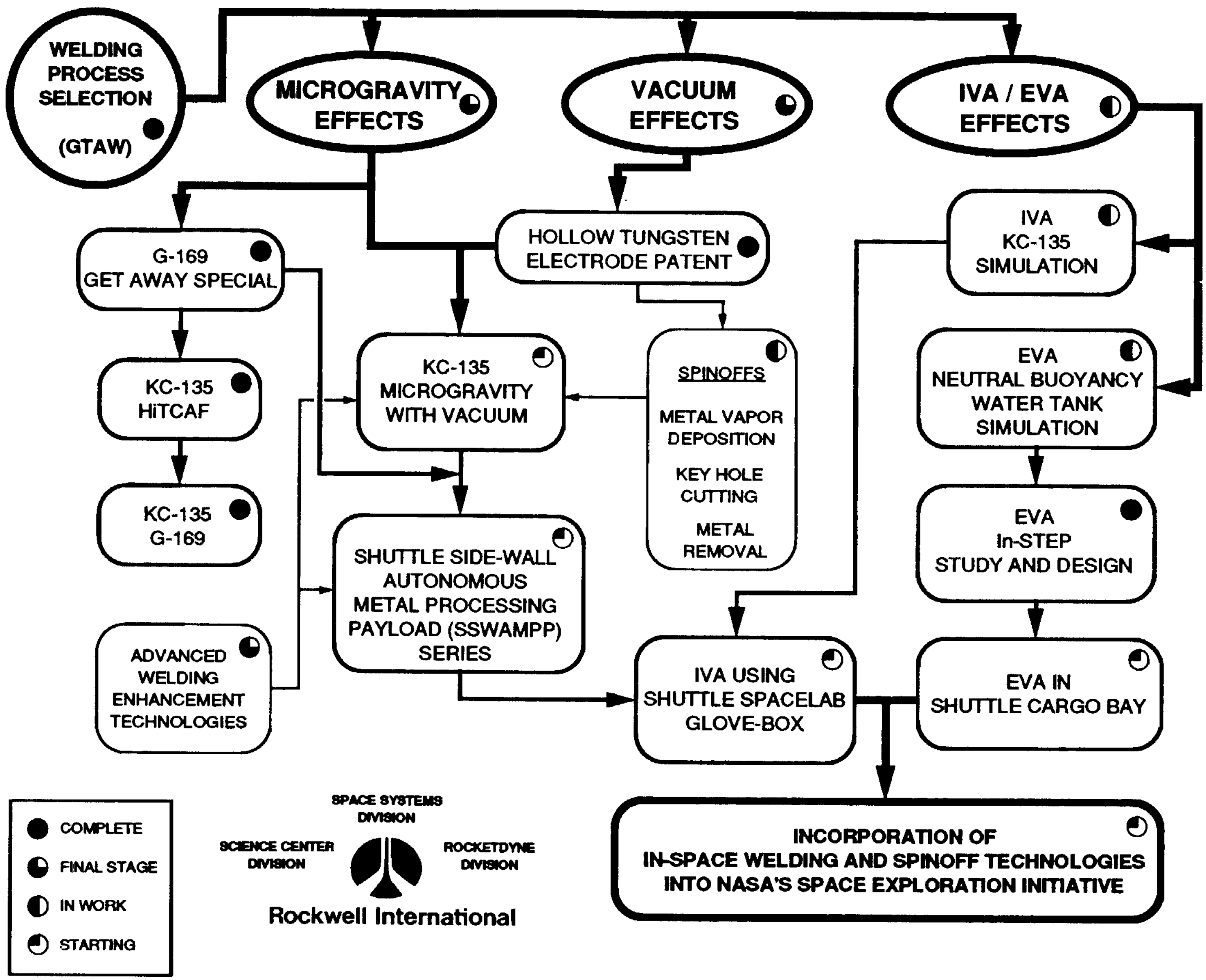


Figure-4: Proposed Rockwell International Path to In-Space Welding and In-Space Metal Processing Spinoffs

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