A Computer-Aided System for Space Welding

by

Takatoshi Nakamura

B.E. Mechanical Engineering (1987) & M.E. Mechanical Engineering (1989)
Keio University, Tokyo, Japan

SUBMITTED TO THE DEPARTMENT OF
CIVIL AND ENVIRONMENTAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

MASTER OF SCIENCE IN CIVIL AND ENVIRONMENTAL ENGINEERING

at the

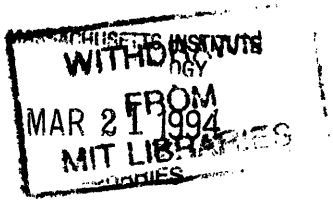
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February, 1994

Signature of Author .....
Department of Civil and Environmental Engineering, February, 1994

Certified by .....
Professor Koichi Masubuch, Thesis Supervisor
Department of Ocean Engineering

Certified by .....
Associate Professor Duvvuru Sriram, Thesis Reader
Department of Civil and Environmental Engineering

Accepted by .....
Professor Joseph M. Sussman, Chairman, Departmental Graduate Committee
Department of Civil and Environmental Engineering



A Computer-Aided System for Space Welding

by

Takatoshi Nakamura

Submitted to the Department of Civil and Environmental Engineering
on September 24, 1993
in partial fulfillment of the requirements for the Degree of
Master of Science in Civil and Environmental Engineering.

ABSTRACT

Since welding is bound to be indispensable for construction of large-scale structures and long-term repairs in space environment, a need for advancement of metals joining process technology is inevitable. However, there exists a tremendous gap between what we must know to successfully achieve activities needed in the future and what we are likely to achieve in the near future. Research on welding which is to take place in space environment is still at its infancy; not many experiments have yet been conducted. Further studies and experiments, along with more experiences, are the key to advancement in the field, but the financial restriction requires efficient research and development processes. Under such circumstances, a computer-aided system is desirable which: 1) Compiles presently available knowledge of effective metals joining processes and 2) determines future research directions.

A knowledge-base ha been created based on most of the currently available information about welding in space and used as a part of the system. The system uses Neuron Data NEXPERT 2.0 as an expert shell, HyperCard 2.0 as a user interface, and Microsoft Excel 4.0 as a numerical database. This system is designed to be expanded to include new knowledge in the future. Two example studies were successfully performed using the system.

Thesis Supervisor: Professor Koichi Masubuchi
Title: Kawasaki Professor of Engineering

Acknowledgments

I would like to express my sincere thanks to Dr. Koichi Masubuchi. His willingness to answer questions and discuss problems exemplifies his dedication as an educator and researcher. His support made this research possible. I would also like to thank Dr. Duvvuru Sriram for giving me important advice at all times.

Dr. Lyman Hazelton was also very important. His knowledge about space development fascinated me and gave me meaningful guidance.

Many thanks go to Dr.Yoshikazu Suita, Dr. Akio Hirose, and Mr. Shinji Koga. Their deep comprehension of welding technology helped me to develop the knowledge -base used in this research.

Finally, I would like to extend special thanks and deep gratitude to my parents and to all the people who have helped me both in studies and private life.

TABLE OF CONTENTS

List of Figures

List of Tables

List of Acronyms and Abbreviations

NASA	National Aeronautics and Space Administration
ESA	European Space Agency
LEO	Low Earth Orbit
PHC	Permanent Human Capability
CIS	Commonwealth of Independent States
EBW	Electron Beam Welding
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
PAW	Plasma Arc Welding
LBW	Laser Beam Welding
EB	Electron Beam
RW	Resistance Welding
FW	Friction Welding
SW	Stud Welding
TW	Thermit Welding
GTAB	Gas Tungsten Arc Brazing

GMAB	Gas Metal Arc Brazing
EBB	Electron Beam Brazing
LBB	Laser Beam Brazing
I	Square
G	Groove
F	Fillet
S	Seam
BUTT	Butt Joint
CORNER	Corner Joint
LAP	Lap Joint
EDGE	Edge Joint
T	T Joint
FRM	Fiber Reinforced Metal
C-C Comp	Carbon Composite

Chapter 1: Thesis Overview

Introduction

Mankind is about to extend its fabrication technology into space. The United States, in cooperation with Canada, the European Community, and Japan, plans to build the space station, *Freedom*, aimed to be completed in a few years, but it is required to be redesigned due to the recent budget cut for space research. The US has decided not to use metals joining processes for on-orbit construction of the space station. However, metals joining processes may be used for maintenance and repair of some parts of the space station. There are several other large projects such as a Moon base project and a solar energy transmission project. In the near future, however, metals joining technology is likely to become indispensable for fabrication of such larger space structures. Although mechanical joining process may be convenient for construction purposes, only welding can repair these space structures. With new possibilities and plans arising constantly, it is important to initiate fundamental research on space welding.

Motivation

The research group of the Welding Systems Laboratory at Massachusetts Institute of Technology has been actively exploring into the field of space welding for the last several years. As a part of this research, currently available metals joining processes are being analyzed for their applicability to the outer-

space environment. After the cold war, more number of the publications about welding in space became available from the former Soviet Union. Duplication of researches must be avoided and the world wide limited budget and resource of man-power for space development should be optimized by collaborating and exchanging the knowledge one another. Therefore, all available information must be collected and integrated systematically.

Integrating the results generated from our experiments and already confirmed welding knowledge in the world, we are presently building a computer-aided system, which determines the realistic overview of currently available welding technology, and thus directs us to clarify the needs for future technology development for space construction.

Objectives

There are three major objectives to develop a Computer-Aided System as follows:

1. To integrate currently available knowledge on metals joining processes in space.

2. To determine the most promising areas of research in space welding processes.

3. To identify realizable welding processes in space, despite the limited availability of information.

Outline of Thesis

Chapter 2 shows an overview of space exploration programs, which have been mainly conducted by the United States of America and the former Soviet Union. Chapter 3 introduces welding that will be one of the most important fabrication technologies in outer space. Several special aspects including mission requirements, space environment, human factors, and management are examined in Chapter 4. Through special considerations stated above, three possible joining processes are suggested and examined in Chapter 5. Chapter 6, 7, and 8 describe a currently developed Computer-Aided System and example studies using this system.

This system is an essential part of "Guide Book for Space Welding" which is being developed by Professor Koichi Masubuchi and the researchers in the Welding Systems Laboratory at Massachusetts Institute of Technology.

Chapter 2: Background

This chapter presents a history of space researches mainly conducted by the US and the former Soviet Union. Then, current space programs including a space station program under discussion are introduced. Finally, a history of welding in space is explained briefly.

2.1 History of Space Research

Since the historical success of the former Soviet Sputnik in 1957, the US has been competing with the former USSR in the field of research, development, and exploration for outer space. Stimulated by the success, American President Eisenhower signed the National Aeronautics and Space Act in 1958 and established the National Aeronautics and Space Administration (NASA). NASA has been successful in launching several satellites both for research purposes such as planetary exploration and commercial use such as long distance communication. The next important step by NASA was the Apollo program with the objective of the first landing on the Moon surface by the human race. After this peak incidence, which used significant cost and man power, NASA was forced to change its attitude to a more conservative one in cost and therefore more profitable for human beings. Extending the knowledge and utilities used in the Apollo program, NASA demonstrated the long-time human flight in the Earth orbit and conducted a lot of research operations including observations with a solar telescope and material processings in the Skylab program.

The former Soviet Union launched a space station, Mir ("peace") from Tyuratam cosmodrome on February 20, 1986. It was placed in a 340 kilometer

high orbit with an inclination of 51.6 degrees. Its initial weight was about 20 tons. Mir was designed to expand its capability to add modules. There were modules added later: 1) an astrophysics module, 2) a technology research and airlock module, and 3) a materials processing and shuttle docking module. A great deal of research including welding experiments have been conducted on this station and some of the data have been disclosed after the cold war.

In 1971 NASA started to develop a new reusable spacecraft called space shuttles which were designed to carry heavier and larger payloads with lower cost, therefore making future space programs feasible and reasonable. Although shuttles were developed successfully, the American government began to reduce funding to space programs due to the overcost of developing shuttles and public criticism through the Reagan and Bush period. There were also indirect reasons such as the end of the cold war and American financial and trade deficits.

NASA also made plans to construct a space station in cooperation with the European Space Agency (ESA), Canada, and Japan. It is the most important project toward future space activities, because it is going to be the next step to enable the sustaining of human activity in space and make possible the accomplishment of research necessary for future space projects.

On July 20, 1989, the 20th anniversary of the first manned landing on the Moon, President Bush made a speech to show the long term goal for the US space program: "...for the coming decade-for the 1990's, Space Station Freedom , our critical next step in all our future endeavors. And for the next century, back to the Moon. Back to the future. And this time, back to stay. And then, a journey into tomorrow, a journey to another planet, a manned mission to Mars." This made our future missions clear.

However, with recent changes in the political party, NASA is under severe pressure to cut its budget and has been asked to redesign the space station smaller in size and with less cost.

2.2 Current Space Programs

2.2.1 Space Station Program

NASA produced a Space Station Task Force in 1982 to construct a permanently manned station in low Earth orbit (LEO). President Ronald Reagan committed the nation to develop it in his speech on January 5, 1984. Canada, the European Space Agency, and Japan joined this project as partners later and this station was named the International Space Station "Freedom". This station is necessary to continue further space programs, since the data about a life support system for human beings and technologies of construction and maintenance will be used.

According to "Space Station Freedom Media Handbook" (by NASA public Affairs Office, May 1992), the program objectives are as follows:

1. Establish a permanently manned, multipurpose facility in LEO in the 1990's:

2. Enhance and evolve mankind's ability to live and work safely in space;

3. Simulate technologies of national importance by using them to provide Space Station Freedom capabilities;

4. Provide long-term, cost-effective operation and utilization of continually improving facilities for scientific, technological, commercial, and operational activities enhanced by the presence of man in space;

5. Promote substantial international cooperation in space;

6. Create and expand opportunities for private-sector activity in space;

7. Provide for the evolution of Space Station Freedom to meet future needs and challenges;

8. Foster public knowledge and understanding of the role of habitable space system capabilities in the evolution of human experience outside Earth's atmosphere.

Recent budget cuts required NASA to redesign Space Station Freedom which would be achieved with two conditions: 1) constructed with less cost and 2) partially used even before fully constructed. The NASA redesign team showed three options. In early 1993, Vice President Albert Gore appointed the Advisory Committee on the Redesign of the Space Station headed by MIT President Charles M. Vest. They began intensive deliberations on April 22, 1993 and delivered a report to the White House on June 10, 1993. According to the Advisory Committee Final Report, space station costs, including inflation, to develop the various options fully to permanent human capability in the year 2000 or 2001, and to operate the station there after for 10 to 15 years, were calculated:

Option A. Permanent Human Capability (PHC) in October, 2000-$16.5 billion for development. Subsequent operating cost: $1.4 billion a year.

Option B. PHC in December, 2001-$19.3 billion for development. Subsequent operating cost: $1.5 billion a year.

Option C. PHC in January, 2001-$15.1 billion for development. Subsequent operating cost: $1.0 billion a year.

Space Station Freedom. PHC in March, 2001-$25.1 billion for development. Subsequent operating cost: $2.4 billion a year.

Two options (Option A and Option C) out of four plans above were recommended by the panel.

Option A is 281 feet long, 75 feet shorter than the proposed Space Station Freedom (SSF). Its solar panels are 248 feet wide. Its construction would require 16 Shuttle flights and at least 224 hours of extra-vehicular activity (EVA) by astronauts: "the associated risk to successful completion and to flight crew safety are substantial." It would accommodate the Japanese and European Space Agencies modules, and part of the Canadian structure.

Option C, a new design, "is the lowest risk option." It features a 92 by 22 foot, seven story cylindrical core module attached to solar panels. It can be built on the ground and launched by a single Shuttle-derived launch vehicle. It could be permanently manned and operational after 3 to 5 Shuttle flights, and 12 hours of EVA. The international partners including Canada, European Space Agency, Italy and Japan object that "the US core module already provides more payload volume than the current SSF baseline, thus putting in question the real need for the additional payload volume provided by the international Partner modules."

The report concluded, "Option A has an advantage in capability and lends itself to modular built-up." **Option B**, which is the highest risk as well as the highest estimated cost. "Option C is the lowest risk and potentially lower in cost."

Option A is shown in Figure 2.2.1.

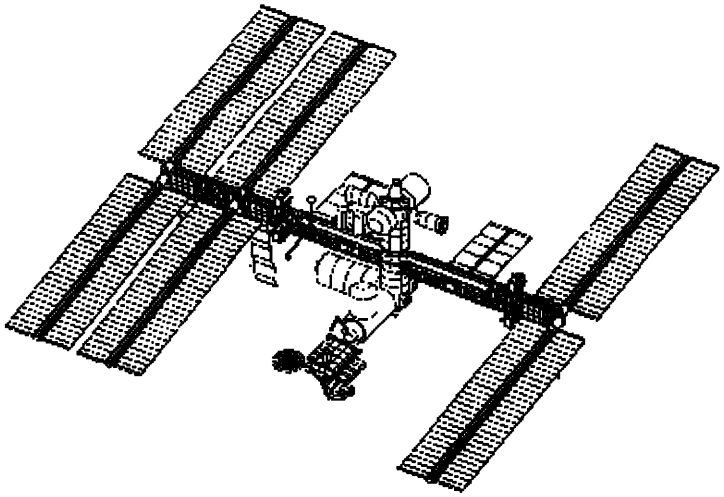


Figure 2.2.1. Space Station Option A

(Source: Advisory Committee Final Report and MIT TECH TALK)

On June 17, 1993 President Clinton approved a revised version of the space station (Option A). However, the space station projects are still under pressure by many people who doubt the merits from the project. Although the most widely discussed option for reducing NASA spending is to cancel the space station, the future space programs will be entirely different from the

current plan, because all manned programs will be based on the data derived from the space station program.

It is also considered to retrieve American old technologies such as Saturn V which can carry payload with less cost and to use the former Soviet technologies which are often more advanced than NASA's in order to reduce total cost for the construction of the Space Station Freedom.

The current plan does not require welding technique to construct the Space Station Freedom. However, welding processes will be necessary to maintain or repair broken parts for long-time use.

2.2.2 Other Space Programs

2.2.2.1 Solar Energy Transmission Program

There have been two primary dreams of the people who support space programs. They are space colonies and solar energy facilities. The former is to the next critical step from the Space Station Freedom, but the latter is still in research level. Solar power is generated with current technologies such as solar panels. However, the transmission of the generated power is now being studied. Some experiments have been conducted in Japan recently. The European Space Agency and NASA have interest in this technology, too. There is possibility to form a new consortium for this research by the three above.

2.2.2.2 Space Exploration Programs

President George Bush showed visionary commitment of future space programs on July 20, 1989, the 20th anniversary of the first manned landing on the Moon. There are three major programs ahead which are: a space station program, a Lunar base program and a Martian exploration program.

Lunar bases will be unmanned first and collect more information to make manned bases in the future. In order to produce larger structures including space colonies and solar power generators, many materials which are not only structural but also important to sustain human's life will be necessary. Table 2.2.1 shows such materials that might be obtained on a Lunar base. Iron, Aluminum and Magnesium are used as structural materials and Oxygen is important to sustain human's life. Glasses are made from Silicon. If most materials are obtained from Moon, it makes future constructions substantially less expensive , because Moon has 1/6 gravity of that of Earth, which makes material carrying cost lower.

Element	Symbol	Percent by weight
Oxygen	O	42.26
Silicon	Si	19.68
Iron	Fe	11.92
Calcium	Ca	8.53
Aluminum	Al	7.20

Magnesium	Mg	4.68
Titanium	Ti	4.65
Sodium	Na	0.35
Manganese	Mn	0.15
Chromium	Cr	0.10
Total		**99.52**

Table 2.2.1. Lunar Mare Constituents

(Source: Apollo mare soil samples)

The US made eight missions to Mars up to and including two failures and two flybys. There were two orbiters (one failed) and two landers. The former Soviet Union also conducted sixteen Mars missions through the end of 1973 and two more in the late 1980's. There were three successful orbiters and three landers (two failed).

The US currently plans a Mars Observer project, mini-lander projects, sample-return projects, and future manned Mars missions. Recent news reported that the Mars Observer, which cost 80 million dollars, was lost on the way to Mars on August 24, 1993 and hardly recovered. In addition to the US, there are two major countries which are preparing Mars projects. The Japanese are developing an orbiter to be launched in 1999 on the new H2 booster. The Commonwealth of Independent States (CIS) has a plan for a few Mars projects including a 1994 mission that consists of an orbiter, two small landers and two surface

penetrators and a 1996 mission that consists of an orbiter, an instrumented balloon, and a small rover. However, both missions are threatened by funding shortfalls in Russia.

2.3 History of Welding in Space

The former USSR conducted the first experimental welding in space in 1969. The equipment used in this experiment that we called "Vulcan" was fully automated electron beam welding. It showed the stability and adequacy to conduct electron beam melting, welding, and cutting in space environment. Only three material processing experiments were conducted in 1973 by the US in the flying laboratory, Skylab. They were a metals melting experiment, a brazing experiment, and a sphere forming experiment. On the other hand, the former Soviet Union had the advantage of making quite a few experiments using flying laboratories and thermal vacuum chambers between 1970 and 1974 and orbital manned space stations, Salyut from late 1970's to early 1980's and Mir in late 1980's. In 1979 coating deposition processes on different material substrates were studied. In 1984 the first manual welding in outer space was conducted by a Soviet female astronaut. There were several experiments including material coating, alloy brazing, and welding of metals reported to be done from 1985 to 1990.

The Soviets decided to use electron beam welding (EBW) as the most suitable welding method in space environment. They developed multi-purpose EB welding tools (URI from 1 to 3 kW) were used both manually and automatically. An open space fabrication deploying a 12 meter truss was experimented using URI. On the contrary, the US has not decided yet which joining process is the most suitable, because EBW may be harmful to human's health if it is not fully automated. Therefore, the knowledge about material processing available in the world must be integrated systematically to develop our future joining technologies.

Figure 2.3.1 and 2.3.2 show the surface pictures of the titanium alloy specimen welded in outer space by the former USSR and presented to Welding Systems Laboratory at Massachusetts Institute of Technology. Figure 3.1.1 was taken by a video image microscope and Figure 3.1.2 by a scanning laser microscope. Compared to the specimens welded on Earth, their grains are larger and more perfect in shape, i. e. the grain boundaries are tri-symmetric.

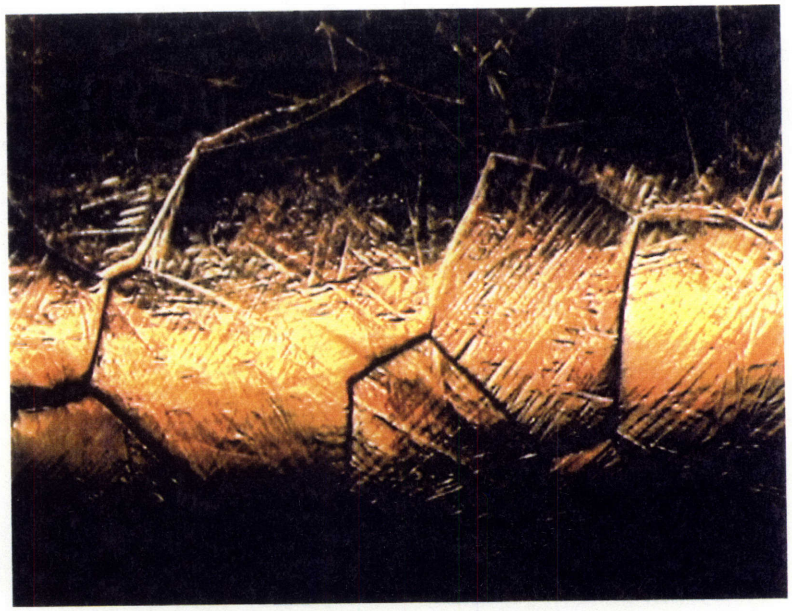


Figure 2.3.1. The surface of Titanium alloy welded in outer space by the former USSR
Magnification: 84 times
(Observed at MIT Welding Systems Laboratory)

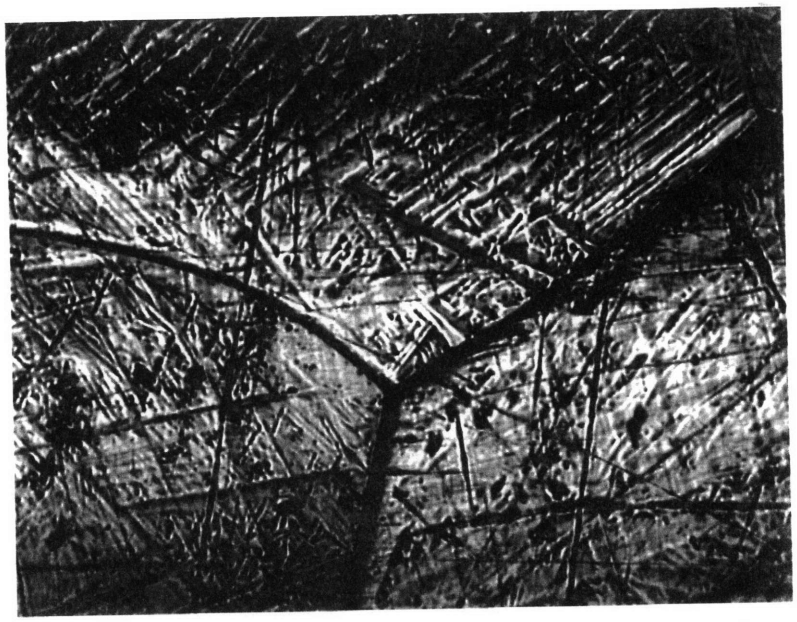


Figure 2.3.2. The surface of Titanium alloy welded in outer space by the former USSR

Magnification: 226 times

(Observed at MIT Welding Systems Laboratory)

Chapter 3: Introduction to a Computer-Aided System for Space Welding

Welding has indispensable advantages over other joining techniques and great deal of possible applications in space. In order to develop this technology, currently available knowledge needs to be integrated. This chapter describes why welding technique is desired and how it will be used.

3.1 Needs of Space Welding

3.1.1 Advantages of Welding

The current plan of on-orbit assembly of the Space Station Freedom project does not require welding processes, instead mechanical fasteners will be used. However, welding will be definitely needed for future repairs of the space station and constructions of larger structures including Lunar bases and space colonies. The change of joining techniques for constructions of space structures may follow the history of ship building.

A ship was originally built using rivets and bolts to joint its parts. Since the invention of welding technique, welding processes have replaced rivets and bolts. Despite initial failures in welded ships, welding joints are used intensively, because they have indispensable advantages over rivets and bolts, which are as follows:

1. Water tightness

2. Light weight, less material

3. Structural strength

4. Less time and cost for fabrication.

These reasons may be applied to future history of joining processes for space structure constructions.

Similarly, welding has essential advantages over other joining processes such as mechanical joining for the following reasons:

1. Air tightness

   Although all manned modules of the Space Station Freedom which must be airtight are planned to be built on Earth, air tightness must be sustained for repair and maintenance. If the whole structures are constructed in outer space, air tightness will be the most important feature in the jointed parts. Mechanical seals can be used to preserve airtight integrity of the space structures, but welding can provide more reliable and permanent seals.

2. Light weight, less material

   Welded joints weigh less and require less material than mechanical joints. When structures are constructed in the Earth orbit or other locations in outer space, materials are provided from Earth, Moon, Asteroids, or other planets. Therefore, it is important to minimize the weight of materials in order to reduce costs.

3. Structural strength

Welded joints can be assumed to have the same structural strength as the material itself. Since welded parts often have more rigidity than the base metal, original shapes of the structures are held and the loads can be transmitted with rigid joints. Mechanical joints cannot be small if the joints are made as rigid as the material itself and may become loose over the service life of the structures. Welded joints have higher strength over a wide range of temperature than mechanical joints and adhesive bonding.

4. Less time and cost for fabrication

Welding requires less time and cost to prepare joint materials than mechanical joints. And also, it achieves the needed structural strength with less materials and therefore reduces huge cost for fabrication.

3.1.2 Possible Applications of Space Welding

3.1.2.1 Construction

Most large structures on Earth cannot be constructed without using welding. Buildings, ships, airplanes, and automobiles use welding as well as mechanical joints. For future fabrications of large structures welding will play an essential role as it does for on-earth structures.

3.1.2.2 Repair and Maintenance

There are dangers for having structural damages. They would be caused by contacts with other structures or space vehicles, or collisions with debris in space or meteorites. The experiments conducted in or near the structures may damage the structures. Even in routine maintenance structurally failed parts of the structures would be replaced or fixed. From the current study, astronauts are expected to conduct 2,200 hour maintenance annually for the planed space station.

3.2 Integrating Knowledge of Space Welding

3.2.1 Necessity of Knowledge-Base System for Space Welding

Historically, many experiments and studies relating to space welding have been conducted by people all over the world. Especially most on-orbit experiments have been carried out by the former USSR. Some of the results have been classified, while others have been published. In order to maximize the information and avoid the duplication of studies under limited resource of man-power and budget, all available information must be collected and integrated systematically.

A knowledge-base system for space welding is suggested and presented in this thesis. This whole system is called "A Computer-Aided System for Space Welding" and planned to be provided to researchers all over the world in the future. This system will grow with more knowledge and help future studies about space welding.

3.2.2 Helping Decision of Future Work

The computer-aided system will be used not only to integrate all available knowledge about space welding but also to help the researchers think which research subjects are necessary to further develop space welding technologies. The system can provide the information on reasons why specific joining processes are the practical space applications.

3.3 Applications of Knowledge-Base System

3.3.1 Instruction Systems for Astronauts

In general astronauts are assumed to be novices in welding. Therefore, astronauts must be trained prior to flights or instructed on-orbit welding sites. Instructions can be made either by the remotely located experts or computer-aided systems including artificial intelligence. The next scheduled space shuttle in the next month will carry the first artificial intelligence developed by a MIT research team. Their system is loaded on the reengineered powerbook which is based on the product of Apple Computer, Inc. The computer-aided system is also developed on the Apple product to keep consistency.

3.3.2 Brains of Automated Welding Robotics

In order to increase productivity, welding processes will be fully automated in the future. The former Soviet Union has already developed automated welding tools, but these tools do not have brains to think and conduct welding for themselves. They must be placed at the welded part accurately and controlled by astronauts. Fully automated welding robotics will be developed and used for any welding use at any location. They will determine the suitability of a welding process, prepare for welding, conduct welding, and do after-treatment. For those purposes robotics must have brains (artificial intelligence).

3.3.3 Space Welding Guidebook

Welding Systems Laboratory at Massachusetts Institute of Technology is developing a guidebook on space welding by collecting and analyzing all the relevant information on currently published in the world All currently available knowledge is being collected and explained in the book. It may be used by all researchers dealing with space welding technologies. The Computer-Aided System is a core of this guidebook.

Chapter 4: Special Considerations for Space

Special aspects must be considered to apply welding technology to space. Expected missions to use this technique are specific in space. Since space environments are different, welding processes must be developed to fit to the environments. Human factors and management aspects are also important elements to be considered. This chapter describes important subjects developing practicable welding processes to be used in space.

4.1 Mission Requirements

4.1.1 Location

Depending on the location of welding operations, the environment, financial restrictions, and available resources at site would greatly vary. For example: in space, we can consider Sun's light to be one of the energy sources; on Moon, we may find some minerals to be used as resources for our mission; the atmosphere surrounding Mars may be useful, or it may affect our choice of welding processes.

4.1.2 Intra/Extra Vehicular Activities

Even if two missions are to take place on the same planet, our choice on fabrication processes still may vary, depending on whether the mission is to be performed inside or outside of the space structure or station. The

environment factors such as pressure and temperature are different, and time allowed for the specific mission task would also vary.

4.1.3 Task

A space mission may involve one or more of the three major tasks: construction, maintenance, and repair. Construction and maintenance can be planned ahead, but since repairing is generally required when accidents occur, it is difficult to predict the extent of damage or procedures for repair until the crew actually reaches the location. For the crew to realize the appropriate procedure, we can do one of three things: 1) provide a fully compiled manual; 2) educate one of the crew members to become an expert on welding procedures; 3) load a knowledge-based expert system on board.

4.1.4 Welding Design

Just as on the earth, possible joining processes vary according to design conditions such as: thickness, joint types, welding positions, weld types, and materials. The severity of restrictions on these parameters would increase in space, so possible joining processes would also become quite restricted. For example, to lighten the load, thin aluminum plates must be used extensively.

4.1.5 Material

Light weight materials such as aluminum, aluminum alloy, titanium, or titanium alloy are mainly used for space applications to save carrying cost. These materials are not only light but also rigid enough to sustain structures. The material used in the future will depend on availability at the site of welding. For example, aluminum and iron are easily obtained from the soil of the Moon.

4.1.6 Equipment, Power and Time

The budget of the mission, the size of the space station, and the type of the transportation space crafts determine the realistic size and weight of equipment, consumables (i.e., shielding gases or filler metals), power, and allocated time. Equipment size and weight also depend on the level of currently available technology.

4.1.7 Accessibility

Depending on the location of the mission, we must determine if it is accessible by man, robot, or manipulator. We must design the space structures so that we can reach any point at any time by one of these accessing methods. There is a need to supply a module which enables installing an appropriate manipulator on the space station, such as an aeronaut mobilizing equipment.

4.2 Space Environment

4.2.1 Microgravity

There is almost no gravity in the space environment unless provided artificially; the physical phenomena that we are accustomed to on Earth, such as heat convection and buoyancy, do not exist or are reduced to the minimal in space. We can therefore obtain a melted metal with uniformly distributed components and mass. This implies that a perfectly crystallized metal will be formed when solidified. However, gas that arises within the molten metal would not be able to escape because of the lack of buoyancy within the metal; this is one of the defective characteristics of the space-solidified metal.

4.2.2 Pressure

Because, in space environment, the atmospheric pressure is considered non-existent, we can easily avoid oxidation of the joined parts and generation of gases within. In this respect, space is an ideal welding environment. Furthermore, processes which generally require a special vacuum welding chamber, such as electron beam welding (EBW), can be greatly facilitated in space, for there is no need for such a chamber. However, processes such as arc welding that are widely available on Earth may experience difficulty, for the vacuum environment obstructs generation of arcs.

Spacecraft and space stations usually have an increased pressure of about one atmosphere to enable the crew members to survive. EBW is thus

not a realistic method in such an environment, and safer and cheaper processes such as arc welding are more appropriate.

4.2.3 Temperature

As stated earlier, atmospheric pressure is close to zero in the space environment. There is no obstruction (i.e., air) between Sun and structures in space, so the sun beam directly strikes the structure surfaces. The lack of air also signifies that the heat radiation interactions that usually occur between an object and air are not present in the space. This magnifies the heat radiation originating from the space structures; the temperature gap between the sunlit surface and shadowed area is known to be 340K (-184F to 428F), and effects such as thermal distortion and metal solidification are inevitable. Furthermore, some welding processes depend highly on the surface temperatures of the metals, thus extra heating treatments may become necessary in shadowed regions.

4.2.4 Possible Contamination and Interferences

Those welding-related problems that are considered minor on Earth (i.e., generations of chemical substances, noise, heat, radiation, and sparks) can possibly become harmful in closed environments, like space stations. For example, electrical noise and x-ray may distract computerized equipment such as measuring instruments and computers. Chemical substances may be harmful to human bodies. Shielding gases (i.e., Argon and Helium) used in gas arc welding processes are by themselves harmless, but these gases may

alter the air configuration in a closed chamber. This may also become a disturbance to human bodies.

4.3 Human Factors

4.3.1 Survival

Performing metals joining processes may affect the crew's health. To avoid such side effects, we must either prepare special protective devices or eliminate such possibility by finding a new technique which enables the crew to work hazard-free.

4.3.2 Operator

Whether to let a man perform the welding process or to use a robot makes a difference. Even if we choose to use a robot, the degree of automation determines how many and how long astronauts must participate in the processes. (Table 4.3.1)

Manual	Unaided IVA/EVA, with simple (unpowered) handtools
Supported	Requires use of supporting machinery or facilities to accomplish assigned tasks (e.g., manned maneuvering units and foot restraint devices)
Augmented	Amplification of human sensory or motor capabilities (powered tools, exo-skeletons, microscopes, etc.)
Teleoperated	Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site (remote manipulator systems, teleoperators, telefactors)

Supervised	Replacement of direct manual control of system operation and computer-directed functions although maintaining humans in supervisory control
Independent	Basically self-actuating, self-healing, independent operations minimizing requirement for direct human intervention (dependent on automation and artificial intelligence)

(J. Kevin Watson: "Engineering Considerations for On-Orbit Welding Operations)

Table 4.3.1. Categories of Man-Machine Interaction

4.3.3 Welding Skills and Knowledge

Some welding processes require highly developed skills, while others do not. To select the most appropriate welding process, one must possess well-experienced knowledge. It is necessary to train such an expert or to develop a well-prepared manual or expert system. Also, once the crew member wears a space suit, his/her mobility inevitably becomes limited; we must develop either a more flexible space suit or welding equipment that is easy to use even while wearing the space suit.

4.3.4 Psychological Aspects

Each crew member must possess an ability to make decisions on his/her own, even in an urgent situation. He/she must also be psychologically strong to withstand a possibly lonely mission into space.

Welding processes require precise judgments, so stability of one's mind could become the key to completion of the mission.

4.3.5 Communication

Even if each crew member possesses a strong mind, he/she must be able to communicate to other astronauts and with the headquarters of the operation, which may be on Earth. We need to make sure that all communication devices provided for them are in good working condition, and we must also search for a better device to further facilitate communication, even if the mission is to take place far away from Earth.

4.4 Management

4.4.1 Budget

A major problem with the space welding technology is that what needs to be known far more exceeds what is already known. Although through the years man has developed considerable knowledge on metals joining technology through experiments and experience on Earth, our present knowledge on joining technology in space is quite limited. One basic reason for this problem is the huge cost needed to perform welding experiments in space and/or under simulated space conditions. Aside from financial problems, it is still a rare opportunity for one to obtain real experience in welding fabrication in space. If we were to develop the needed space welding technology mostly through experiments and experience, just as we have done for that of Earth, a tremendous cost, manpower and time must be spent. Realistically speaking, considering the financial restraints that many nations face today and in the foreseeable future, these needed resources will not be made available. It is thus important for both engineers and managers involved in research and development activities to expand the space welding fabrication knowledge in a more systematic manner.

4.4.2 Time Allocation

It is the task of the management to allocate time, manpower, and equipment so that each mission can be completed in a most reasonable and

efficient manner; managers must prioritize among the task completion, human life, and financial restrictions.

4.4.3 Risk Management

In space exploration, we must expect many unforeseeable risks or accidents. In some cases the accidents are negligent and thus the mission can be completed without any delay. In other cases, however, the accident or breakage may expose the crew to a life threatening situation, in which case saving lives should definitely have higher priority than completing the mission. In still other cases, the equipment may be broken or resources may be missing somehow; the crew is required to attempt to complete the task with a limited amount of tools and machinery. These risk management procedures must be established, and the equipment or tools needed in the steps must be prepared and provided well in advance, so that the crew is able to determine what is expected of them in an urgent situation.

Chapter 5: Possible Joining Processes in Space

There are three types joining processes that are suggested: welding, adhesive bonding, and mechanical joints. Each process has advantages and limitations; therefore, the most suitable one must be used depending on the case. This chapter explains those joining processes.

5.1 Welding

There are more than 100 welding processes known to date. The space welding research group of the Welding Systems Laboratory at Massachusetts Institute of Technology has selected 13 processes with high future feasibility for welding in space.

5.1.1 Gas Tungsten Arc Welding (GTAW)

GTAW is an inert gas-shielded joining process using an electric arc generated between a tungsten electrode and a workpiece. Inert gases including argon and helium are used as the shielding gas. Welded materials are stainless steels, aluminum alloy, titanium alloy, and many others. The arc of this method is so stable that even thin plates can be welded. The welding speed is not fast. It has a cleaning effect in welding in the reversed polarity (the electrode plus). In case additional metals are required to the welded part, filler metal is provided. Figure 5.1.1 shows the principle of GTAW.

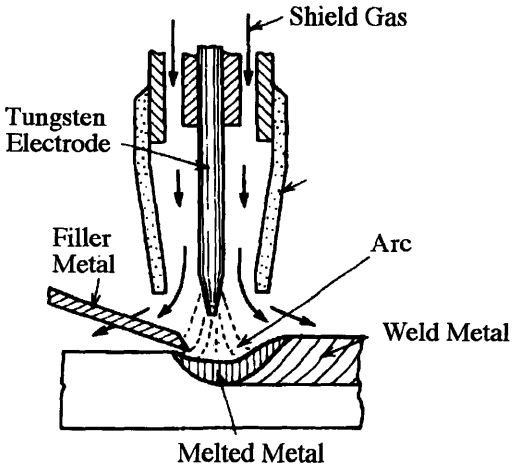


Figure 5.1.1. Principle of GTAW

5.1.2 Gas Metal Arc Welding (GMAW)

GMAW is one form of gas arc welding which uses inert gases to protect the heated workpiece and weld metals and the electric arc. As a consumable electrode metals are used. The metals are transferred from an electrode to the workplace in globular drops or sprays (fine droplets).

There are experiments of GMAW by the former Soviet Union on Soyuz-6. By the reference 128, some results are as follows:

1. At low current, molten drops grew large and remained attached to the electrode for a long period of time

2. Increasing the current increased the electromagnetic pinch effect

3. Stable metal transfer was achieved when using the short circuit technique or impressed current

4. Weld beads bulged slightly in the center due to surface tension, resulting in decreased weld penetration

5. When welding in a vacuum, it was possible to achieve a stable arc in the vapor of the electrode material.

5.1.3 Plasma Arc Welding (PAW)

PAW is also one of arc welding processes. It uses plasma gases which are hot ionized gases as well as shield gases to produce high temperature, more concentrated and more controllable arcs. Figure 5.1.2 shows the principle of the plasma arc welding.

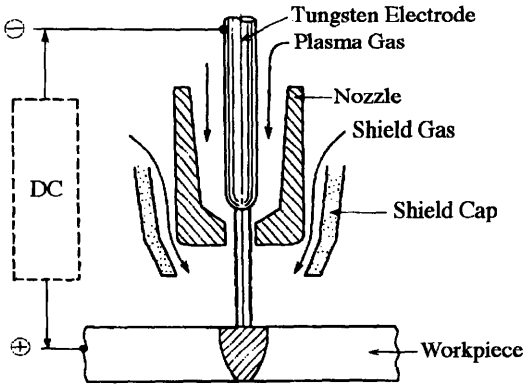


Figure 5.1.2. Principle of PAW

There are experiments of PAW by the former Soviet Union on Soyuz-6. By the reference 128, some results are as follows:

1. Arc ignition, arc stability, and focus of anode spot were affected by the amount of vacuum

2. On thin samples, weld formation was similar to those done on Earth, but in space the formation was dominated by surface tension forces

3. Sound welded joints were obtained

4. Some porosity was found along the fusion line in the titanium alloy

5. Arc constriction was difficult when the chamber was vented into space.

5.1.4 Laser Beam Welding (LBW)

LBW uses a concentrated laser beam, which is coherent light, to generate intense heat needed to melt and join workpieces. LBW is so controllable that welding of very small parts (micro welding) is possible. The energy density is very high (10^6~$10^8 W/cm^2$), and LBW does not require shielding gases. LBW can be conducted regardless of surrounding pressure. Laser beams are used for heat treatment, brazing, soldering, cutting, and coating. Laser beam brazing will be mentioned later.

5.1.5 Electron Beam Welding (EBW)

EBW uses an electron beam (high velocity electrons) to generate heat. An electron beam is concentrated by electromagnetic coils. EBW requires vacuum conditions. Outer space naturally has an ideal condition for this requirement. EBW is the welding method that the former USSR decided to use for welding in space. EBW makes deep penetration which enables one pass welding even for a thick workpiece. Heat input is usually small and deformation is minimized. EBW is also very controllable.

The experiments using EBW aboard Skylab showed some findings by the reference 128:

1. The feasibility of performing EB welding, cutting, and melting in microgravity conditions was proven.

2. The Skylab samples showed that the grain shapes were larger and more elongated than the ground-based specimens. This indicates a major difference in heat convection during solidification of metals.

3. The Skylab specimens had more symmetrical sub-grain patterns, while ground-based specimens showed orientation with the solidification front.

The experiments of EBW were performed by the former Soviet Union on Soyuz-6. By the reference 128, some results are as follows:

1. The weld shape and degree of penetration were similar to that of ground based samples.

2. Sound welded joints were achieved using all materials.

3. There was a slight increase in the porosity of the aluminum alloy sample, most likely because of the lack of a significant gravity gradient to produce buoyancy forces.

4. Electron beam cutting of all materials was proven.

After the comparison of three welding processes: EBW, GMAW, and PAW, the Soviet space program chose EBW as the most suitable welding method because of its versatility and inherent energy effectiveness.

5.1.6 Resistance Welding (RW)

RW uses electrical resistance and mechanical pressure on the contacted small parts of workpieces. Heat is generated by the passing of high current (1,000~100,000 Amps) through the contacted points. There are several kinds of RWs such as spot welding and projection welding. These are easily automated and used in the industries, because it is fast and easy. Figure 5.1.3 shows the principle of RW

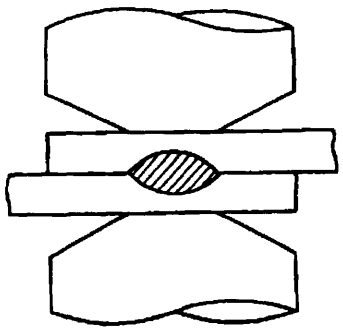


Figure 5.1.3. Principle of RW

5.1.7 Friction Welding (FW)

FW is a relatively new welding process and uses heat generated by mechanical friction. The typical FW is shown in Figure 5.1.4. Friction is produced by rotating one workpiece and pushing the other piece to it. FW does not require heavy equipment.

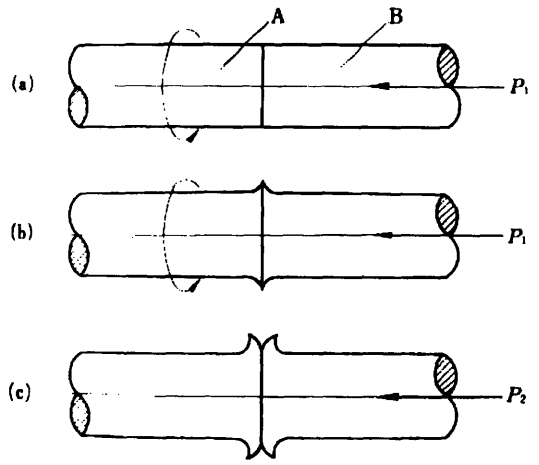


Figure 5.1.4. Principle of FW

5.1.8 Stud Welding (SW)

SW is the process to joint studs to workpieces. There are three types of SW in terms of the way of heat generation. They are arc stud welding, percussion stud welding, and resistance stud welding. The former two types of welding are widely used and the principles are shown in Figure 5.1.5 and 5.1.6.

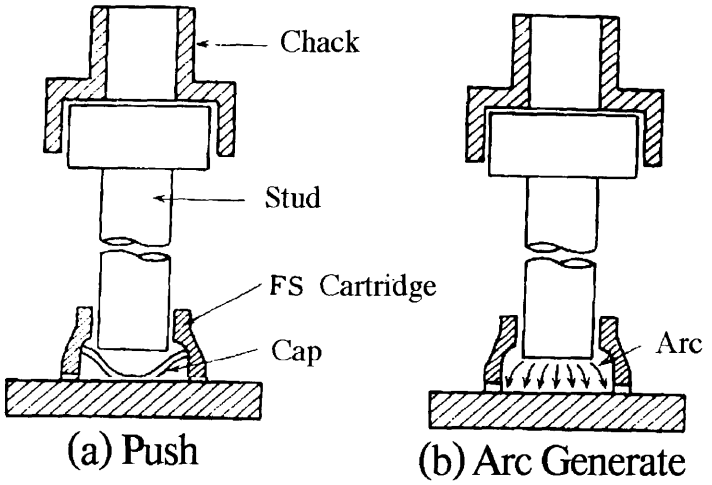


Figure 5.1.5. Principle of arc SW

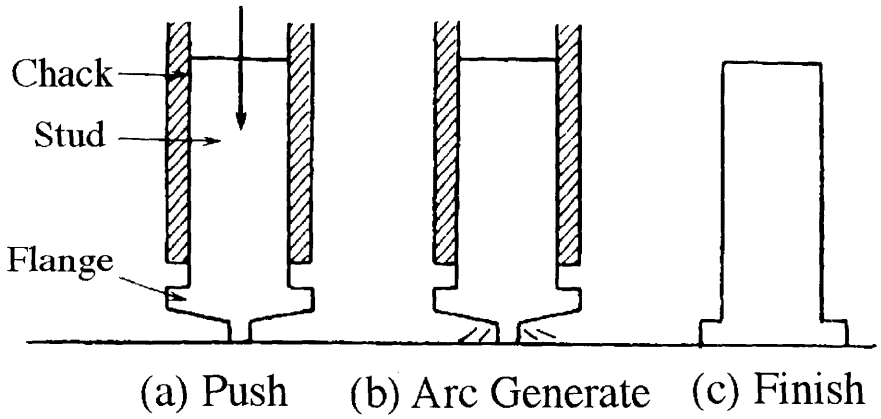


Figure 5.1.6. Principle of percussion SW

5.1.9 Thermit Welding (TW)

TW is the welding method to use chemical reaction of metal oxides and aluminum to generate heat which can be 3,100°C theoretically. The reaction is as follows:

$$3Fe_3O_4+8Al=9Fe+4Al_2O_3 \quad (5.1.1)$$

$$Fe_2O_3+2Al=2Fe+Al_2O_3 \quad (5.1.2)$$

$$3FeO+2Al=3Fe+Al_2O_3 \quad (5.1.3)$$

TW is easy to be used and does not require heavy equipment and electricity, thereby saving cost. The preparation is minimum.

5.1.10 Gas Tungsten Arc Brazing (GTAB)

Brazing is the oldest and simplest welding process. It is to melt the metal which has relatively low melting temperature and put it on the joining workpieces. Brazing uses wetting, special characteristics of metals. Brazing is distinguished from soldering in terms of temperature they use. Brazing uses the higher temperature than 450°C, while soldering uses the lower temperature than that.

The experiment relating to brazing was conducted by the US aboard Skylab. Thermochemical brazing using the heat generated by the chemical reaction was used in this experiment. The results obtained can be summarized as follows:

1. The wetting and spreading characteristics of the brazed samples were superior to those produced on Earthresulting in better filling of the gaps.

2. The Skylab joints had fewer defects and less porosity than welds made on Earth, showing that quality was better.

3. There seems to be no upper limit to the size of gaps that can be brazed in space, therefore joints with large fit-up tolerance can be brazed.

4. Brazing can complete with welding for many space applications where only welding would normally be considered.

GTAB is one of brazing processes and it uses gas tungsten arc (GTA) to generate heat. Therefore, GTAB has the same conditions as GTAW.

5.1.11 Gas Metal Arc Brazing (GMAB)

GMAB is also one of brazing processes, and it uses gas metal arc (GMA) to generate heat. Therefore, GMAB has the same conditions as GMAW.

5.1.12 Electron Beam Brazing (EBB)

EBB is also one of brazing processes, and it uses gas metal arc (EB) to generate heat. Therefore, EBB has the same conditions as EBW.

5.1.13 Laser Beam Welding (LBW)

LBB is also one of brazing processes, and it uses gas metal arc (LB) to generate heat. Therefore, LBB has the same conditions as LBW.

5.2 Adhesive Bonding

Adhesive bonding is widely used in many industries including aerospace, ship, electronics, computer, camera, and automobile, due to its ease of use. Adhesive bonds are developed for specific purposes and improved recently. The feasible bond for construction, repair, and maintenance in outer space is that for structural use and must have the same reliability and rigidity as welding. However, adhesive bond has a serious disadvantage. It cannot sustain the expected strength over a wide range of temperature. Therefore, it is not possible to use in outer space right now. Adhesive bonding may be used for space applications sometime in the future when its quality and performance are improved.

5.3 Mechanical Joints

Mechanical joints are planned to be used for the construction of the space station "Freedom," because the reliability and feasibility of welding and adhesive bonding have not been assured yet. However, joints of future space structures will be made using these three joining techniques.

Chapter 6: Knowledge-Base for System

The Welding Research Group at MIT has been collecting for years the publications associated with welding in space. These information was integrated in the computer using a database software. Then, it was translated into a programmable form for computers and used in a Computer-Aided System for space welding. This chapter describes the integrated database on space welding and the translated knowledge.

6.1 Database for Space Welding

All currently available publications about welding in space were collected to develop a database was created. It was produced on FileMaker Pro by Claris Corporation. In References the database is shown in the format of bibliography.

Table 6.1.1 and Figure 6.1.1 show the number of publications about welding in space in terms of key words. The total number is 160

Key Word	Number
Adhesive Bonding	2
Automation	9
Construction	10
Electrostatics	1
Experiment	9
Micro-gravity	2
Low-pressure	16
Management	2
Material	22

Metal-transfer	1
Mission	11
On-orbit-operation	7
Plan	19
Power	4
Safety	1
Structure	1
Thermal-effect	3
Welding	40
Total	160

Table 6.1.1. Number of publications about welding in space in terms of key words

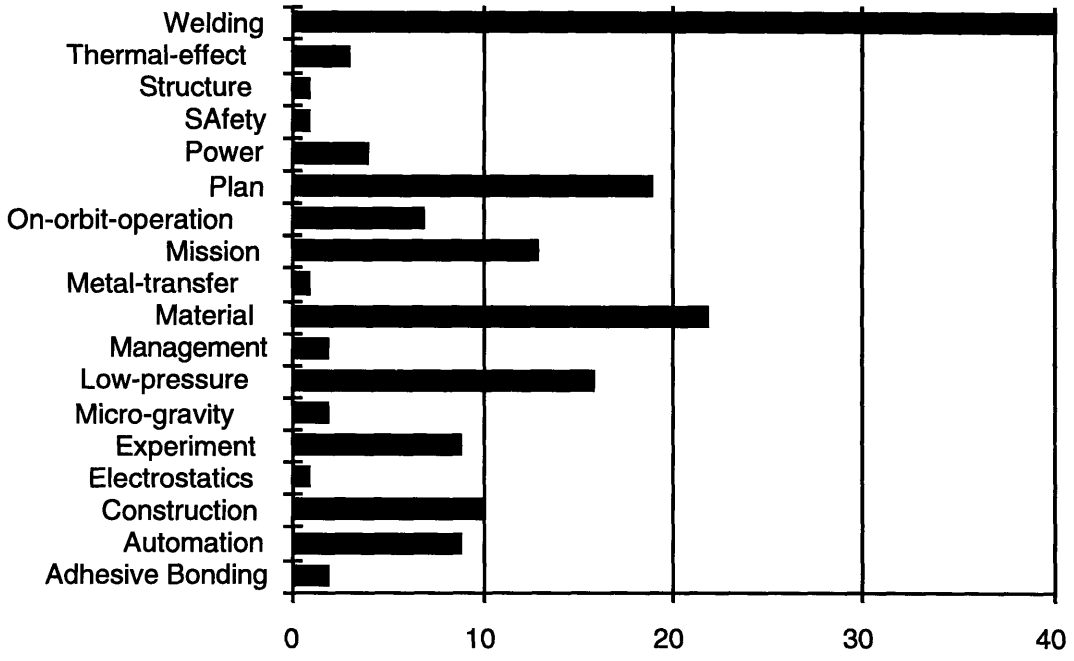


Figure 6.1.1. Number of publications about welding in space in terms of key words

Most publications are written about space activities or research relating to welding in general. More research associated with a specific area such as a low pressure welding or practical materials in space must be conducted to develop welding technologies practically usable in space. The computer-aided system for space welding is designed to assist us in allocating the limited resources including man-power and budget to more important areas than others.

6.2 Building Knowledge-Base of System

It is necessary to translate the knowledge collected as the database into a programmable form for a computer. Although all the aspects considered in Chapter 4 must be included in the knowledge-base of the system theoretically, only limited information is available to date. Therefore, the developed system provides not all information that is theoretically necessary to complete the system but a standard platform with limited knowledge. The system can be expanded by incorporating information or knowledge that become available.

The present system includes weld types, joint shapes, joint types, workpiece thickness, material, power capacity, equipment weight, microgravity, pressure, temperature, and possible contamination and interferences.

6.2.1 Welding Processes

The present system includes thirteen welding processes as follows:

(1) Gas Tungsten Arc Welding (G.T.A.W.)

(2) Gas Metal Arc Welding (G.M.A.W.)

(3) Plasma Arc Welding (P.A.W.)

(4) Laser Beam Welding (L.B.W.)

(5) Electron Beam Welding (E.B.W.)

(6) Resistance Welding (R.W.)

(7) Friction Welding (F.W.)

(8) Stud Welding (S.W.)

(9) Thermit Welding (T.W.)

(10) Gas Tungsten Arc Brazing (G.T.A.B.)

(11) Gas Metal Arc Brazing (G.M.A.B.)

(12) Electron Beam Brazing (E.B.B.)

(13) Laser Beam Brazing (L.B.B.)

6.2.2 Joint Types and Weld Types

Five joint types used in the system are shown in Figure 6.2.1.

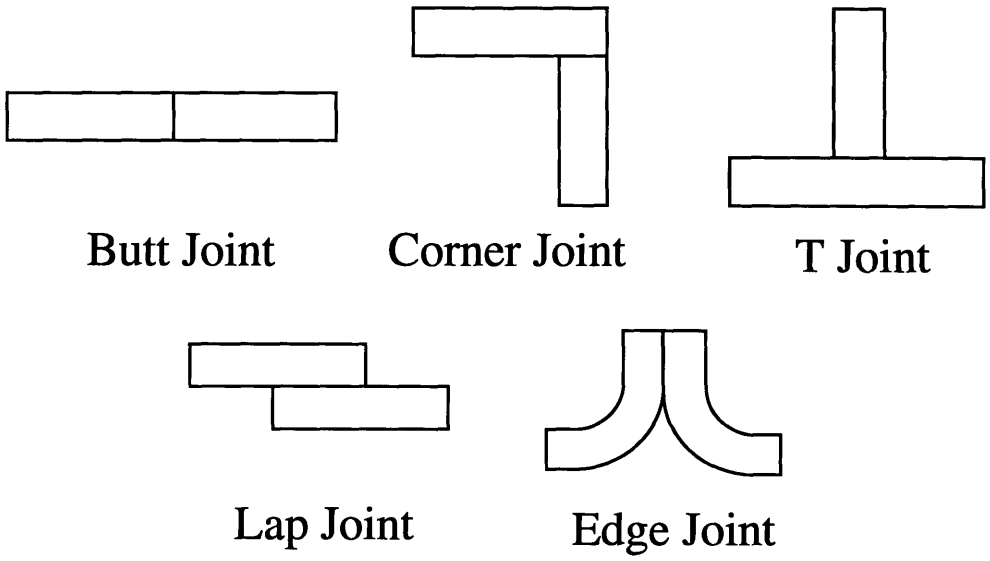
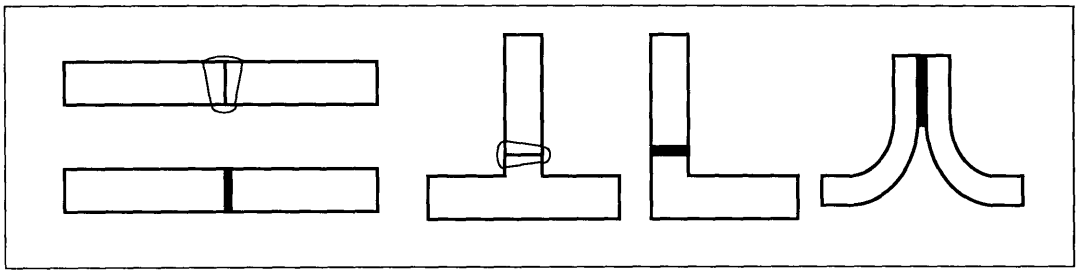
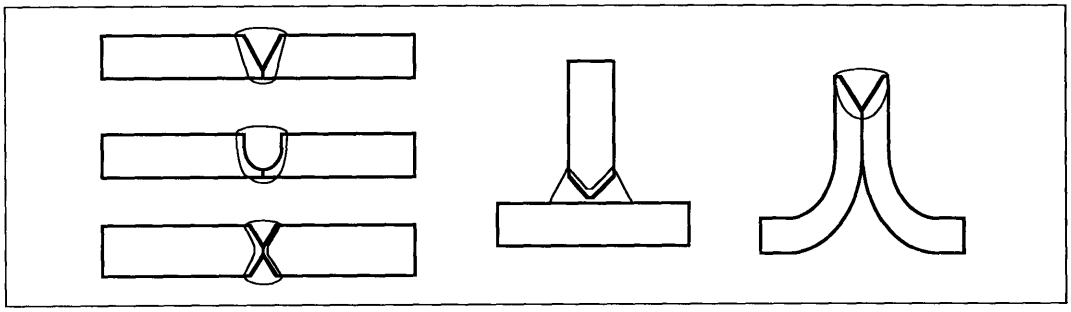


Figure 6.2.1. Joint Types

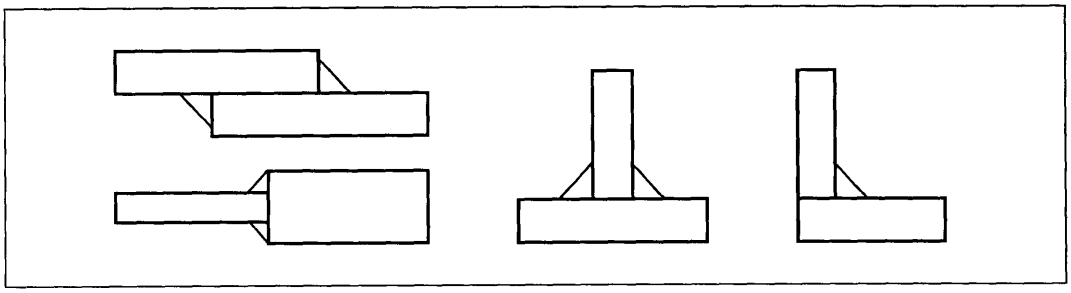
Four weld types used in the system are shown in Figure 6.2.2.



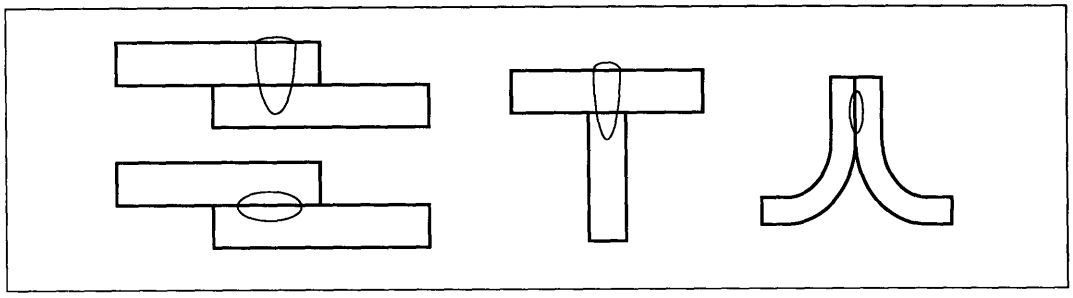
Square (I)



Groove (G)



Fillet (F)



Seam (S)

Figure 6.2.2. Weld Types

Table 6.2.1 shows the relations between joint types and weld types. O means compatible and X means incompatible.

	Joint Type					
		BUTT	CORNER	LAP	EDGE	T
Weld Type	I	O	O	X	O	O
	G	O	O	X	O	O
	F	X	O	O	X	O
	S	X	O	O	O	O

Table 6.2.1. Relations between joint types and weld types

6.2.3 Thickness

Three categories of thickness are analyzed here. Table 6.2.2 shows relations between those categories of thickness and joint types for each welding process. The meaning of the symbols in the table are as follows:

	Joint Type				
	BUTT	CORNER	LAP	EDGE	T
GTAW	ABC	ABC	ABC	ABC	ABC
GMAW	ABC	ABC	ABC	ABC	ABC
PAW	AB	AB	AB	AB	AB
LBW	AB	AB	AB	AB	AB
EBW	ABC	ABC	ABC	ABC	ABC

RW	na	na	A	A	na
FW	ABC*	na	na	na	ABC*
SW	na	na	na	na	AB**
TW	AB	na	na	AB	na
GTAB	A	A	A	A	A
GMAB	A	A	A	A	A
EBB	A	A	A	A	A
LBB	A	A	A	A	A

Thickness A: Less than 4 mm

B: From 4 mm to 10 mm

C: More than 10 mm

Note * Available only for Tube-to-Tube, Cylindrical Bar-to-Bar, Tube-to-Plate, and Bar-to-Plate welding processes

** Available only for Cylindrical Bar-to-Plate welding process

Table 6.2.2. Relations between thickness and joint types for each welding process

6.2.4 Materials

Table 6.2.3 shows the availability of each welding process. Five materials including steel, aluminum (aluminum alloy), titanium (titanium alloy), Fiber Reinforced Metal (FRM), and Carbon Composite (C-C Copm) are considered here.

	Materials

	Steels	Aluminum	Titanium	F.R.M.	C-C Comp
GTAW	S	S	S	na	na
GMAW	S	S	A	na	na
PAW	S	S	S	na	na
LBW	S	A	A	na	na
EBW	S	S	S	na	na
RW	S	S	S	na	na
FW	S	S	A	na	na
SW	S	S	A	na	na
TW	S	A	na	na	na
GTAB	S	S	S	S	A
GMAB	S	S	S	na	na
EBB	S	S	S	S	A
LBB	S	S	S	S	A

Note S: Suitable A: Available na: Not available

Table 6.2.3. Suitability for each welding process

6.2.5 Joint Shapes

Joint Shapes are categorized into three, (1) plate-plate joints, (2) pipe(bar)-pipe(bar) joints, and (3) pipe(bar)-plate joints as shown in Figure 6.2.3.

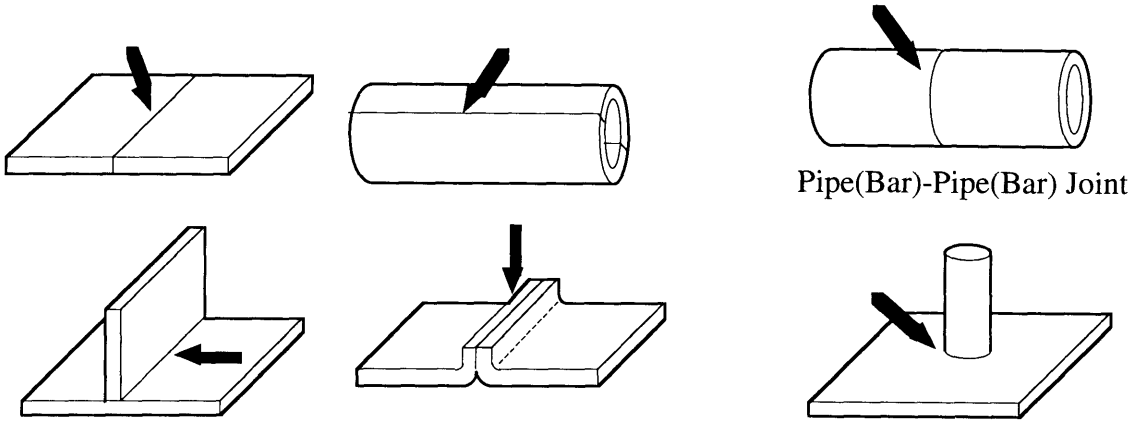


Figure 6.2.3. Joint Shapes

	Joint Shapes		
	Steels	**Aluminum**	**Titanium**
GTAW	S	S	S
GMAW	S	S	S
PAW	S	S	S
LBW	S	S	S
EBW	S	S	S
RW	S	S	S
FW	S	S	A
SW	S	na	na
TW	S	S	S
GTAB	S	S	S
GMAB	S	S	S
EBB	S	S	S

LBB	S	S	S

Note S: Suitable na: Not available

Table 6.2.4. Availability of joint shapes for each welding process

6.2.6 Welding Skill

Each welding process requires a certain level of skill of welding. Table 6.2.5 shows the level of the level of welding skill for each welding method.

	Welding Skill		
	Expert	**Intermediate**	**Titanium**
GTAW	F	np	np
GMAW	F	np	np
PAW	F	np	np
LBW	F	np	np
EBW	F	np	np
RW	W	F	np
FW	W	F	np
SW	W	F	np
TW	W	F	np
GTAB	F	np	np
GMAB	F	np	np

EBB	F	np	np
LBB	F	np	np

Note W: Well done F: Fair np: Not possible

Table 6.2.5. Required welding skill

6.2.7 Possible Contamination and Interferences

Several contaminations and interferences are expected to occur and they are often hazardous to human beings and high-tech machines, such as computers and experimental equipment. The system considers five different hazards including arc light, laser radiation, gases, electric noise, X-ray radiation, and metal vapor. Table 6.2.6 shows the expected hazards for each welding process.

	Hazard					
	Arc Light	Laser Radiation	Gases	Electric Noise	X-ray Radiation	Metal Vapor
GTAW	E		E	E		E
GMAW	E		E	E		E
PAW	E		E	E		E
LBW		E	E	E		E
EBW	E			E	E	E
RW				E		

FW				E		
SW	E			E		E
TW						
GTAB	E		E	E		E
GMAB	E		E	E		E
EBB				E	E	E
LBB		E	E	E		E

Note E: Expected

Table 6.2.6. Hazard for each welding process

6.2.8 Equipment Weight and Power Capacity

There are wide range of welding tools in terms of weight and power capacity. And they change as new tools are developed. Therefore, this system does not have specific value about them, but estimated values are put into the system in the form of Microsoft Excel files as shown in Appendices. .

6.2.9 Microgravity, Pressure and Temperature

Currently effects of microgravity, pressure, and temperature are being studied by a number of groups in various parts of the world. Therefore, this system does not have specific numbers about them, but estimated numbers are put into the system in the form of Microsoft Excel files as shown in Appendices.

Chapter 7: Computer-Aided System

A computer-aided system is necessary to provide the knowledge to all the people involved in the development and research on welding in space. This chapter shows details of the system.

7.1 Objectives

The major question is how to select an appropriate approach for research in a field where sufficient knowledge is not yet available. We propose one model with three major objectives which may help researchers and managers in determining the direction and practicality of approach to the future research.

1. To integrate currently available knowledge on metals joining processes in space

2. To determine the most promising areas of research in space welding processes

3. To identify realizable welding processes in space, despite the limited availability of information

7.2 New Computer-Aided System

An expert system is usually a transference of knowledge from a human expert to computers in order for people to make full use of the knowledge. Thus, construction of an expert system generally implies that there exists a human expert; it cannot be applied to an unknown field which does not have enough information. It is a convenient way, however, to integrate substantial amount of knowledge, and the inference engine of the system can refer to any of the knowledge available.

When we consider the metals joining techniques in space, many conditions are interrelated to each other. It is extremely difficult, if not possible, to determine whether or not a certain joining process is applicable in space. We took advantage of an expert system's ability to integrate vast amount of knowledge, and by adding some improvements we constructed our computer-aided system.

Our system's characteristics are:

1. Ease of knowledge addition/deletion

2. Ability to make a selection using currently available data, even if we have only a limited amount of information

3. Ability to show the future research direction by a research indicator, which is attached to each knowledge

4. Its potential to become a real expert in metals joining processes as the knowledge database grows.

7.3 Building the New System

Of all the currently available knowledge, we have chosen those that are indispensable and constructed the prototype using the knowledge-base system discussed in Chapter 6.

We have used estimated values for the parameters on which no exact values are available. We thus cannot expect this system to always produce perfectly accurate output, but we can expect at least to grasp the general tendency of our problems. Figure 7.3.1 depicts this system's general organization. Our prototype uses an Apple Macintosh as the platform with system 7.0.1, NEXPERT OBJECT (released by Neuron Data, Inc.) as the expert system shell, Microsoft Excel as the numerical database handler, and HyperCard 2.0 (supplied by Claris Corp.) as the user interface.

Platform: **Apple Macintosh with System 7.0.1 by Apple Computer, Inc.**

Expert system shell: **NEXPERT OBJECT Version 2.0 by Neuron Data Corporation**

Numerical database: **Microsoft Excel Version 4.0 by Microsoft Corporation**

User interface: **HyperCard Version 2.0 by Claris Corporation**

The knowledge-base has been rewritten as a rule form and then has been inputted to the expert system. A rule is in the form "If --- Then---" One of the main rules used in the system is shown in the following:

If

GTAW.material is not "not available"

And GTAW.thickness is not "not available"

And GTAW.joint_type is not "not available"

And GTAW.shape is not "not available"

And GTAW.welding_skill is not "Difficult"

And GTAW.weld_type is not "not available"

And GTAW.power_capacity is not "not available"

And GTAW.micro_gravity is not "not available"

And GTAW.pressure is not "not available"

And GTAW.temperature is not "not available"

And GTAW.equipment_weight is not "too_heavy"

Then **GTAW.availability** is confirmed.

We used 236 rules in this prototype.

In order to facilitate use of this system, a newly improved user interface has been developed. It has been created on the HyperCard with the special external commands which enable us to communicate between the interface and the core of the system. It introduces the system to users in the beginning of the interface using animation. In order to start the system, a user clicks the start button which initiates the system and loads the data necessary. Then the user

clicks the appropriate figures or buttons according to the situation they face. The system automatically creates the input data, but they can be corrected or added by users later. After this data preparation, the system is run by clicking OK button and it studies the availability for each welding process for the conditions users input. In case that a specific welding process is not feasible for those conditions, the system shows the reasons from which the user can understand the situation which subjects must be studied further in order to obtain the knowledge that he/she wants to obtain. If the problem is solved, the rejected welding process may become one of feasible and promising. All of the user interface is shown in Appendices.

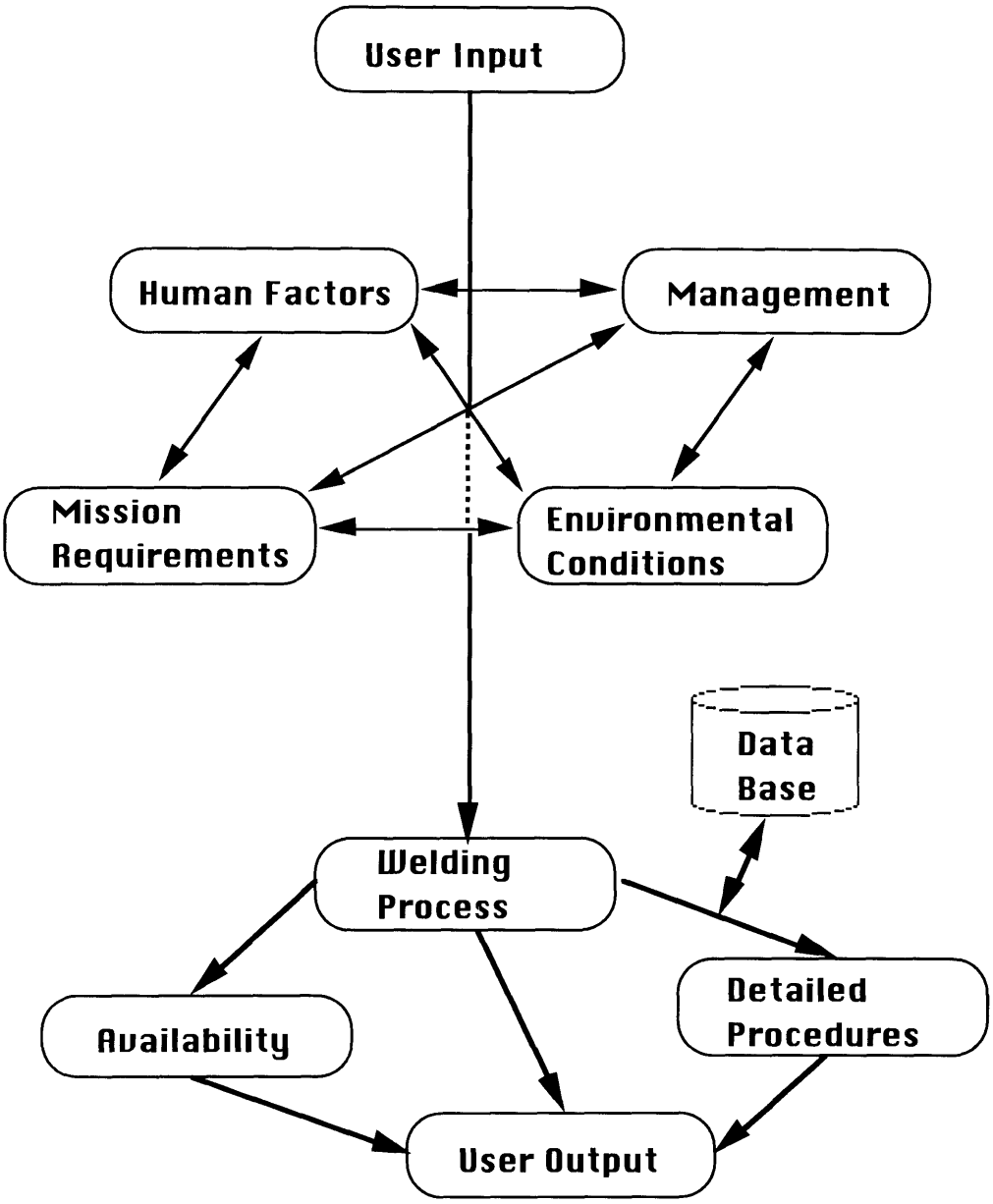


Figure 7.3.1. System Organization

Chapter 8: Analyses Using the Developed System

Two examples are shown using the system in this chapter. One is the situation when the outer shell of the space station needs to be repaired, and the other is when its inner shell needs to be repaired.

8.1 Repair of Outer Shell of Space Station

It is possible that holes or breaks on the outer shell of the space station may be produced by contacts with other structures or collisions with debris in space or meteorites.

Objective

An astronaut repairs the break on the outer shell of the space station under the instruction of experts on the earth.

Location

Outside the space station on the orbit of the earth

Environmental Conditions

Pressure: 0.0 ATM

Gravity: 0.0 G

Temperature: 250 °K

Mission Requirements

Weld type: Square (I)

Joint type: Butt joint

Material: Aluminum

Joint shape: Plate-Plate joint

Workpiece thickness: 2 mm

Allowed power capacity: 50 kW

Allowed equipment weight: 100 kg

Operator: Astronaut with expert help

The results calculated by the system are as follows:

1. GTAW: Not feasible

   Reasons: low pressure, too heavy equipment weight

2. GMAW: Not feasible

   Reasons: low pressure

3. PAW: Feasible

   Hazard: arc light, gases, electric noise, metal vapor

4. LBW: Feasible

   Hazard: laser radiation, gases, electric noise, metal vapor

5. EBW: Feasible

Hazard: arc light, electric noise, X-ray radiation, metal vapor

6. RW: Not feasible

Reasons: unavailable joint type

7. FW: Not feasible

Reasons: unavailable joint shape and power capacity, too heavy equipment weight

8. SW: Not feasible

Reasons: unavailable joint type, joint shape and power capacity too heavy equipment weight

9. TW: Not feasible

Reasons: unavailable power capacity, too heavy equipment weight

10. GTAB: Not feasible

Reasons: low pressure, too heavy equipment weight

11. GMAB: Not feasible

Reasons: low pressure

12. EBB: Feasible

Hazard: electric noise, X-ray radiation, Metal vapor

13. LBB: Feasible

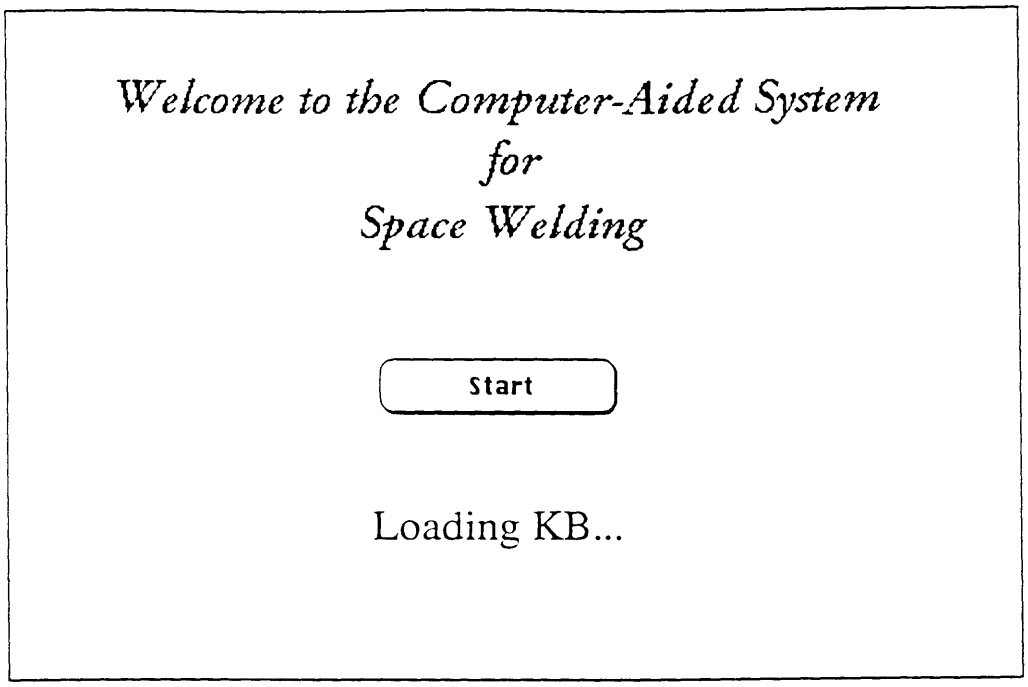
Hazard: laser radiation, gases, electric noise, metal vapor

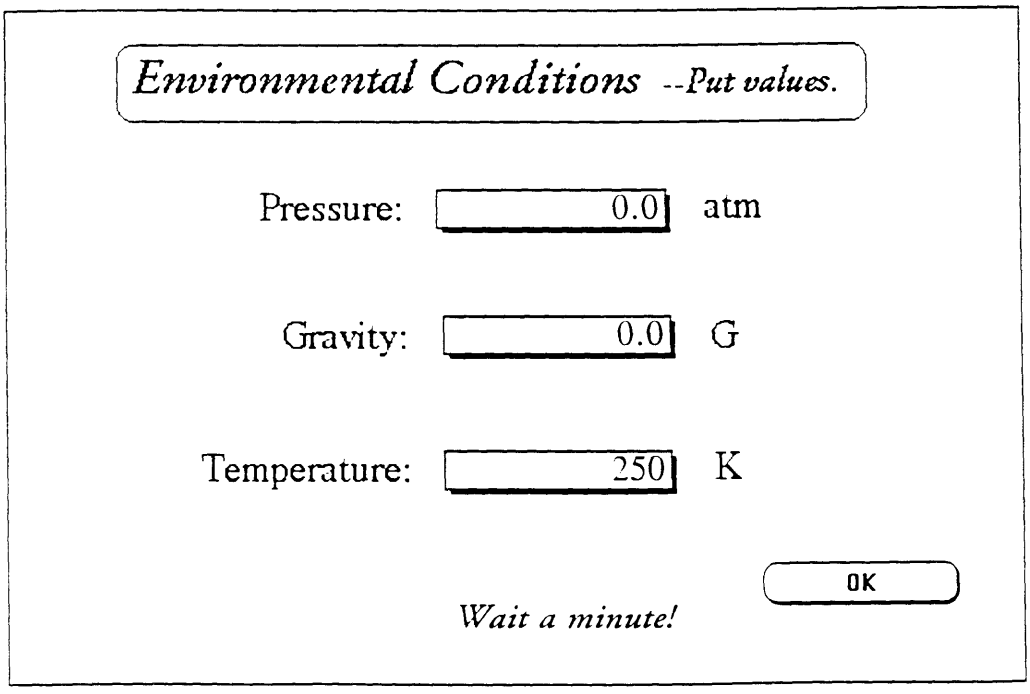
Under the assumed conditions, GTAW is not feasible because of low pressure and too heavy equipment weight. If these two reasons are eliminated by improving GTAW process, GTAW will have great possibility to be a main fabrication process in the future. Therefore, we can say that the most important areas to improve this specific joining process are: 1) to study how to generate and sustain stable arc in vacuum condition and 2) to reduce the weight of the equipment of the process.

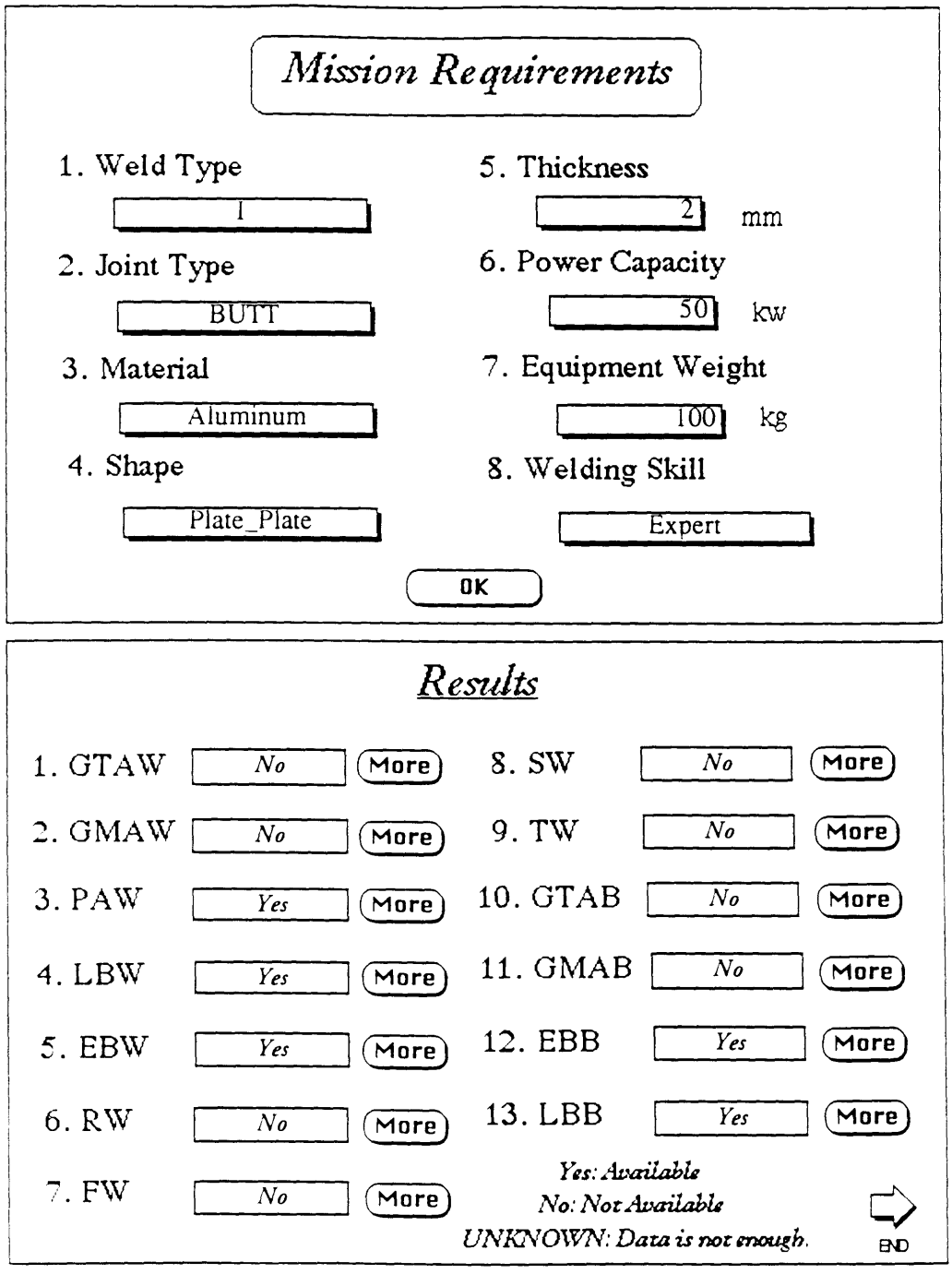
For other processes which are not feasible under the present conditions, the system can study the feasibility of each process and inform the user important areas of future research in the same way as described before.

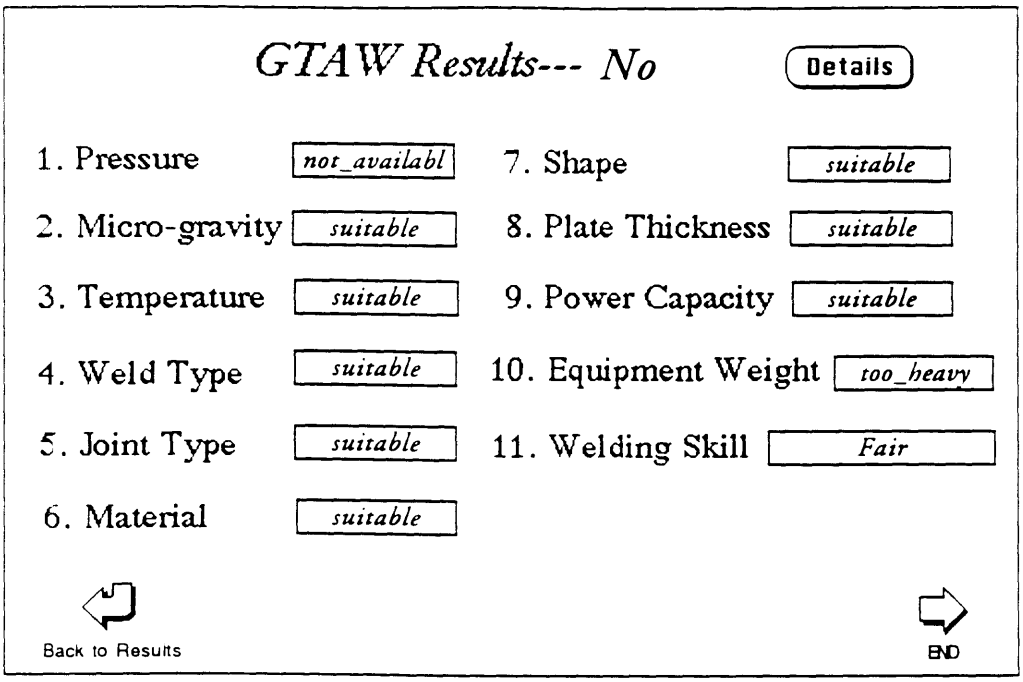
Under the assumed conditions, PAW is feasible, because all the requirements are satisfied. If the process is feasible, the system points out expected hazards by the process. Expected hazards caused by PAW include arc light, gases, electric noise and metal vapor, thus we need protect the humans and high-tech equipment.

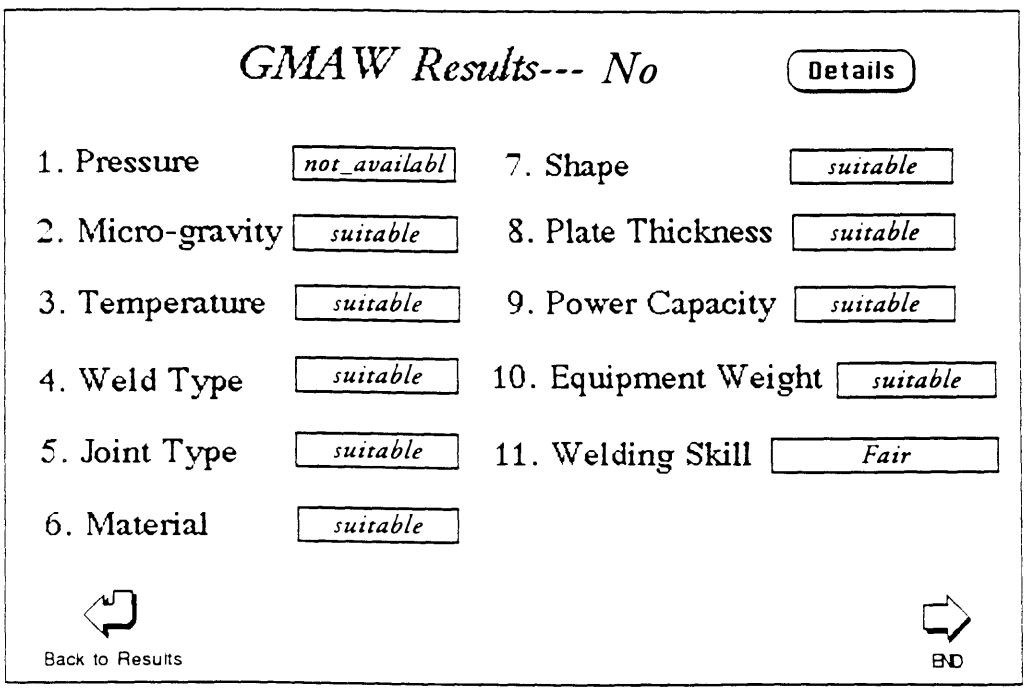
The user interface with which the system conducted a feasibility study is shown starting from the next page.

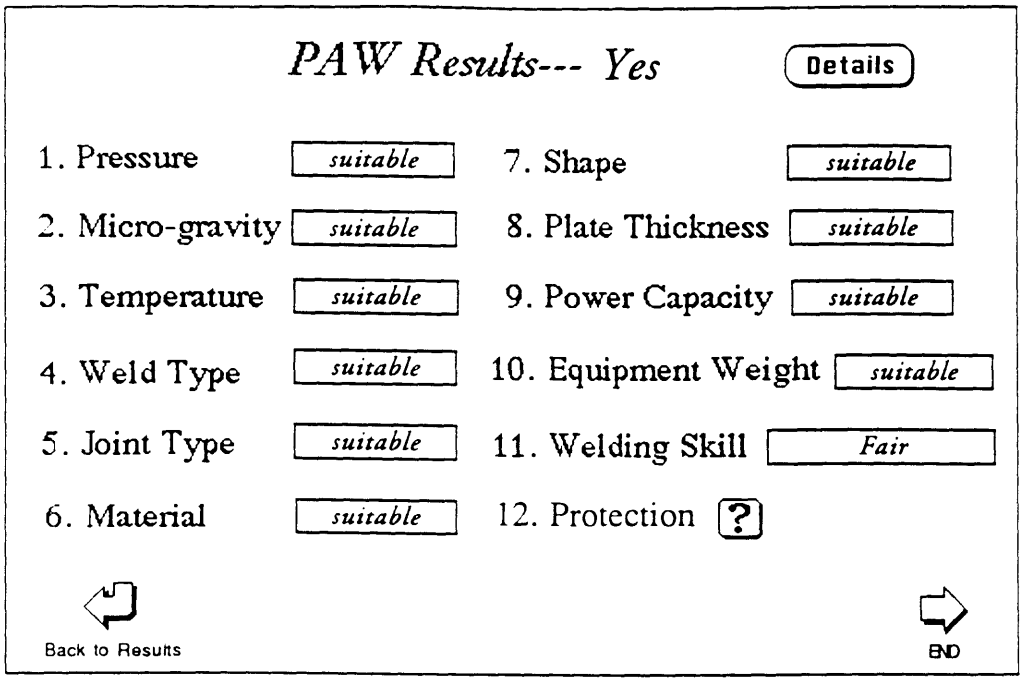

Welcome to the Computer-Aided System
for
Space Welding
Start
Loading KB...

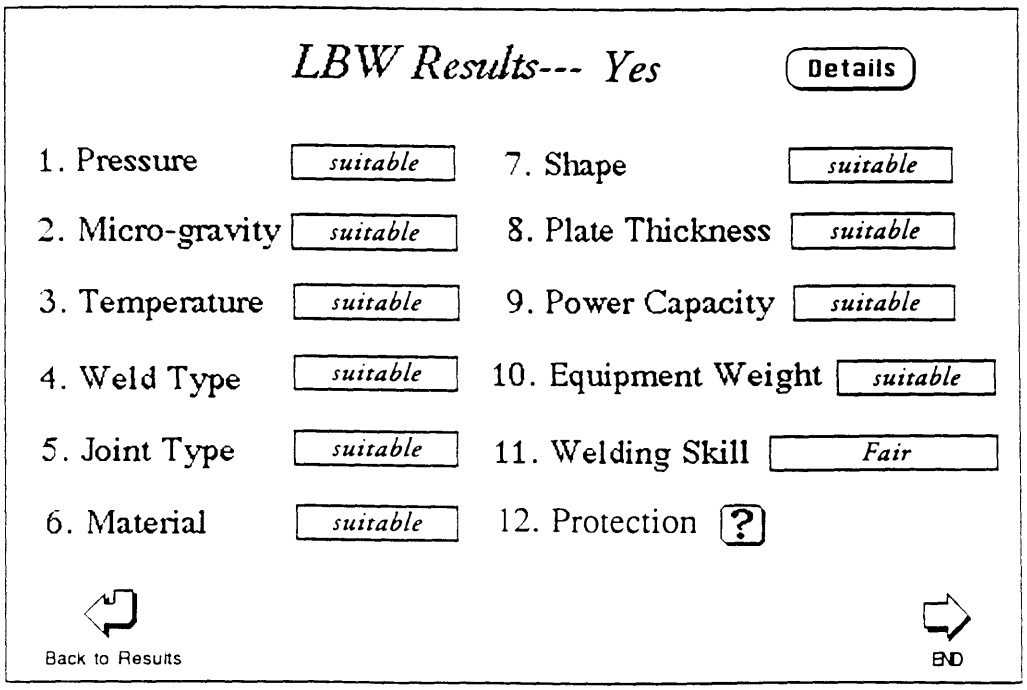

Environmental Conditions --Put values.
Pressure: 0.0 atm
Gravity: 0.0 G
Temperature: 250 K
OK
Wait a minute!

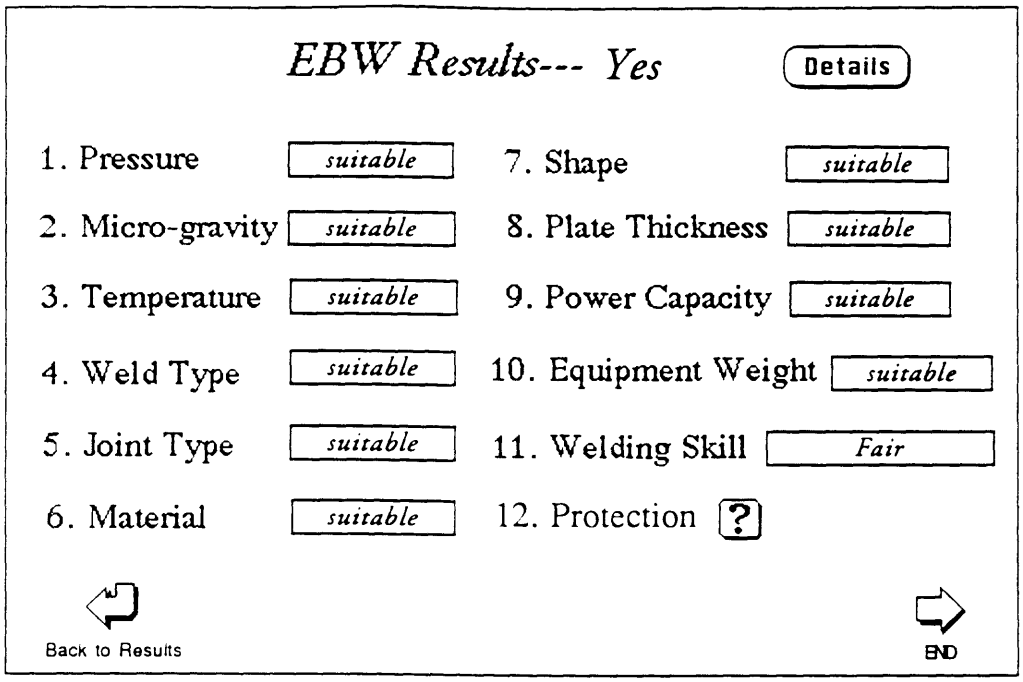

Mission Requirements
1. Weld Type
I
2. Joint Type
BUTT
3. Material
Aluminum
4. Shape
Plate_Plate
5. Thickness
2
mm
6. Power Capacity
50
kw
7. Equipment Weight
100
kg
8. Welding Skill
Expert
OK
Results
1. GTAW
No
More
2. GMAW
No
More
3. PAW
Yes
More
4. LBW
Yes
More
5. EBW
Yes
More
6. RW
No
More
7. FW
No
More
8. SW
No
More
9. TW
No
More
10. GTAB
No
More
11. GMAB
No
More
12. EBB
Yes
More
13. LBB
Yes
More
Yes: Available
No: Not Available
UNKNOWN: Data is not enough.
END

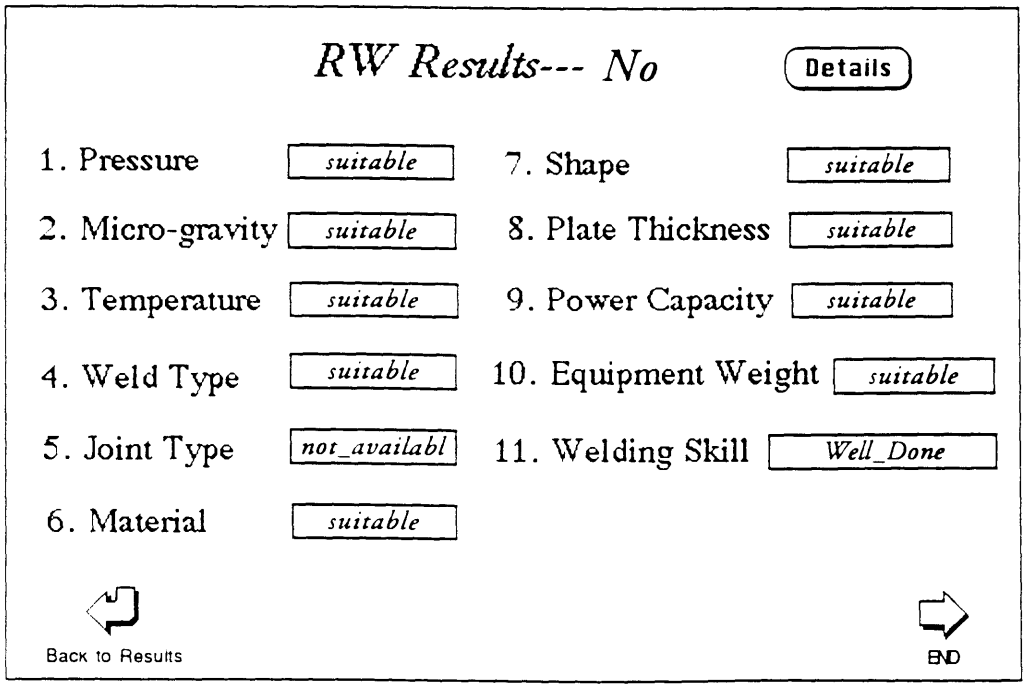

GTAW Results--- No
Details
1. Pressure
not_availabl
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
too_heavy
11. Welding Skill
Fair
Back to Results
END

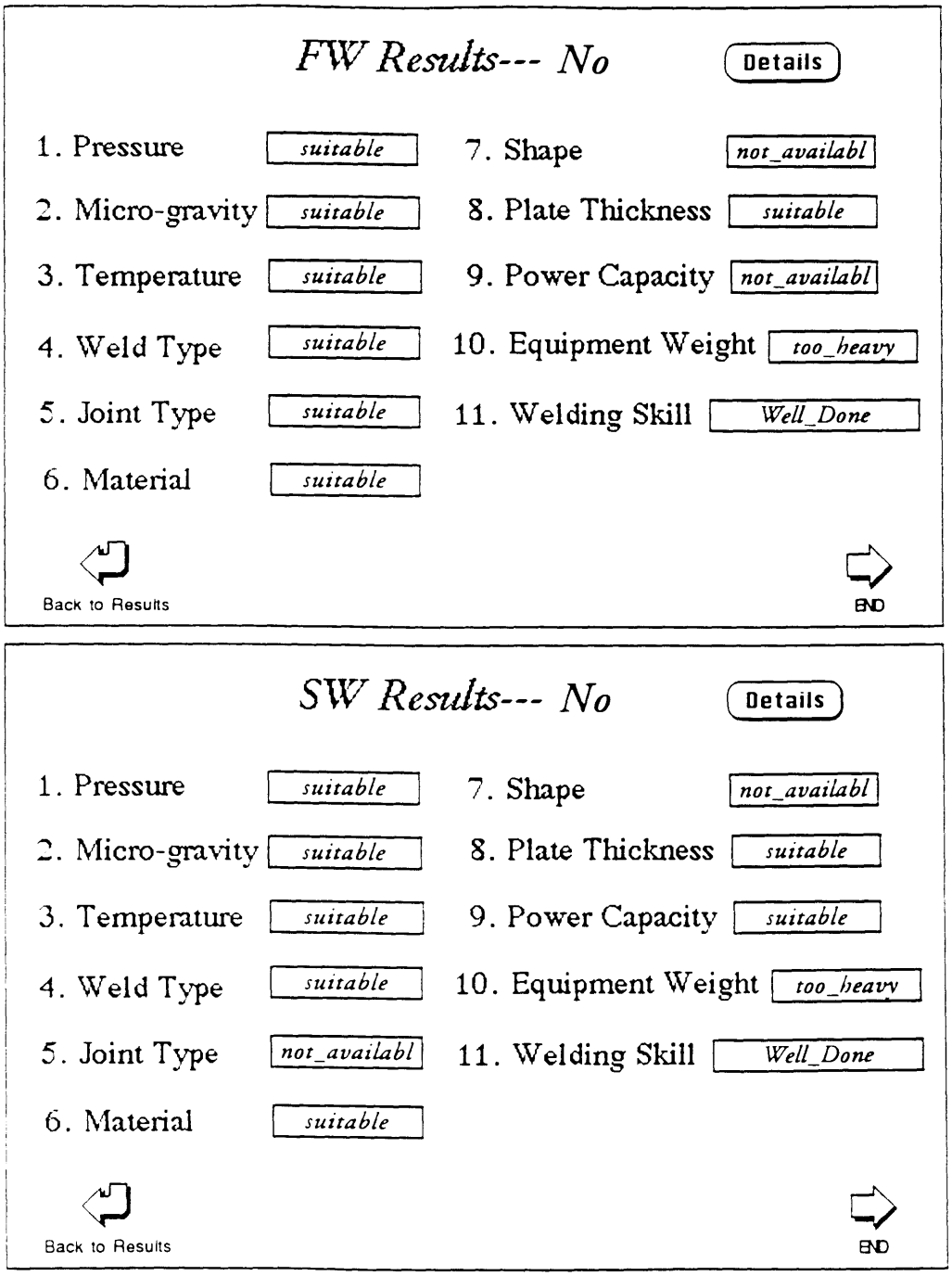

GMAW Results--- No
Details
1. Pressure
not_availabl
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
Back to Results
END

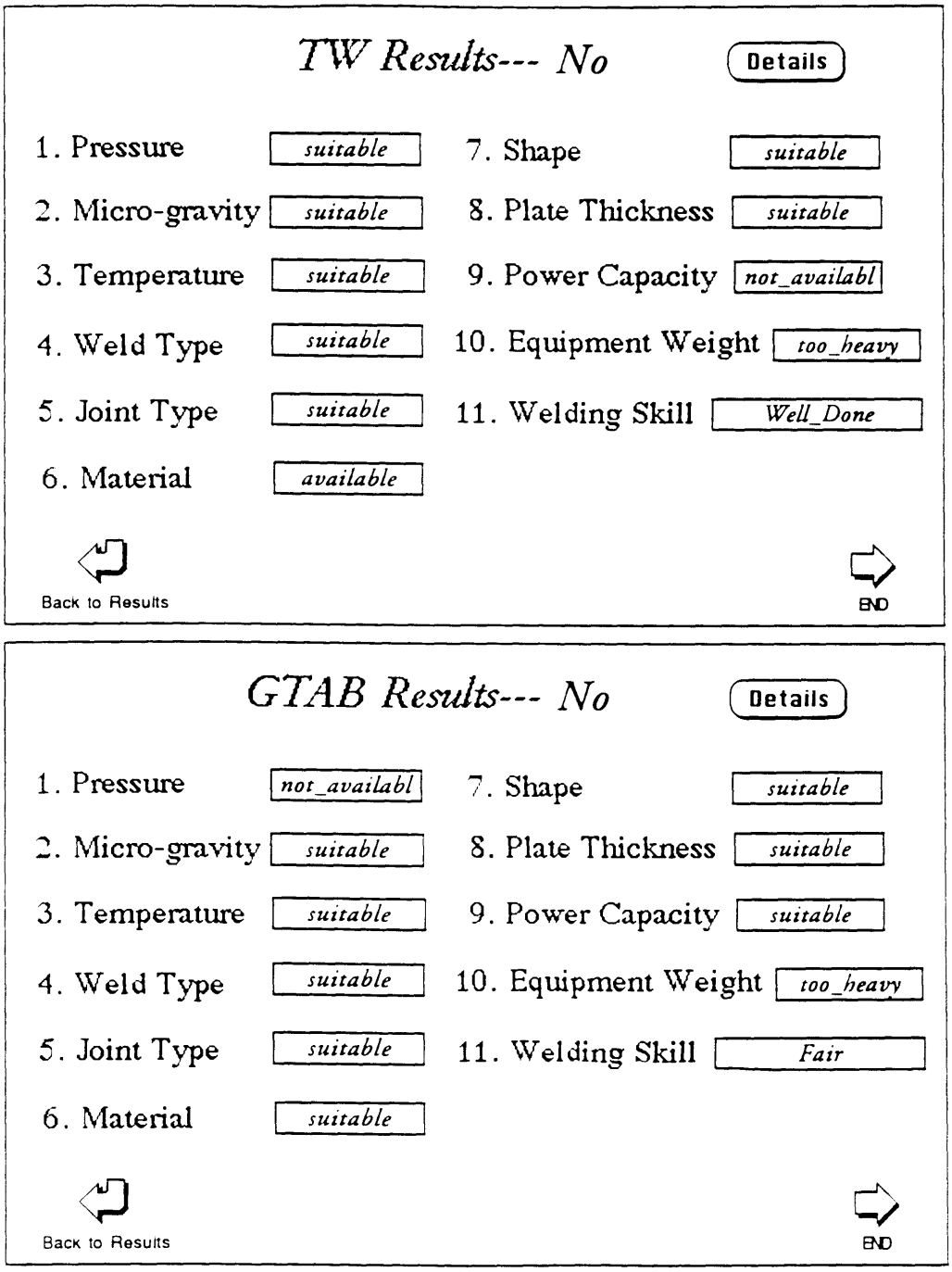

PAW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

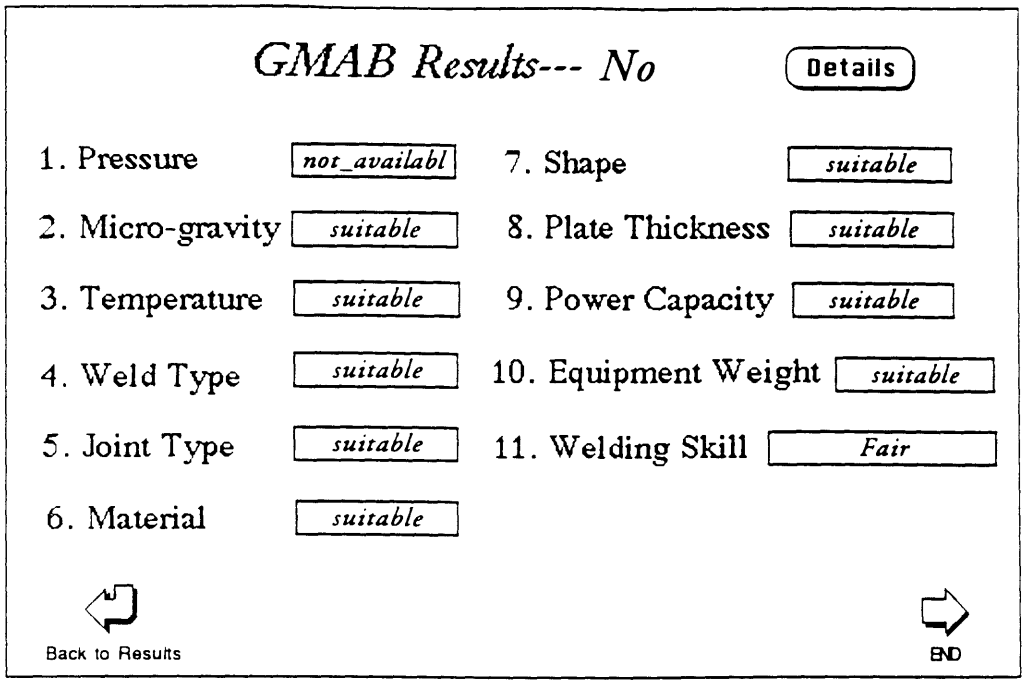

LBW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

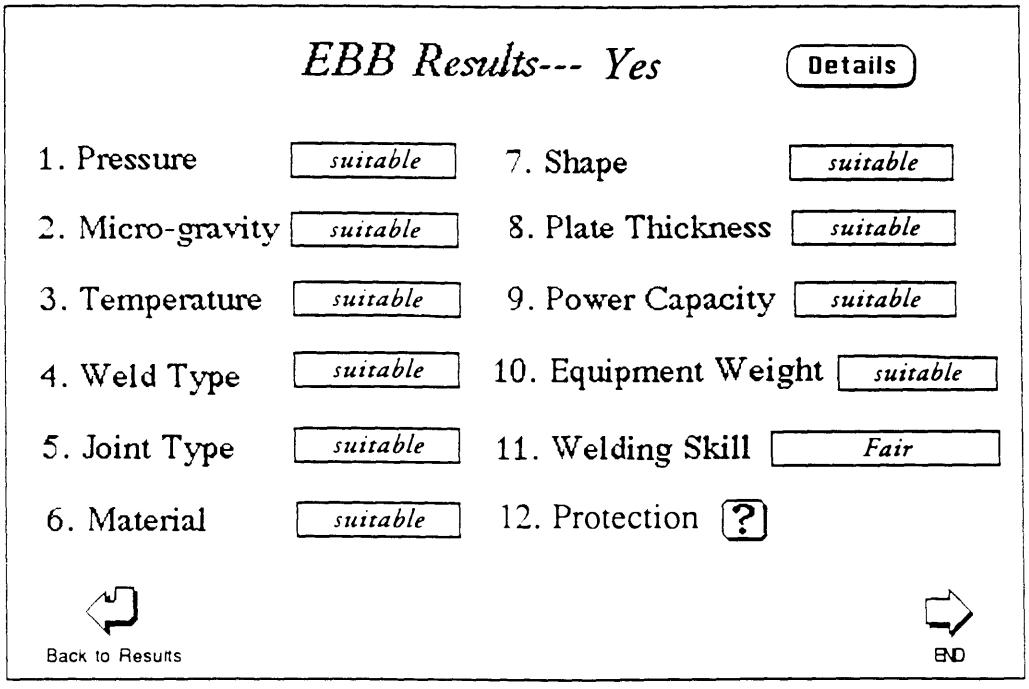

EBW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

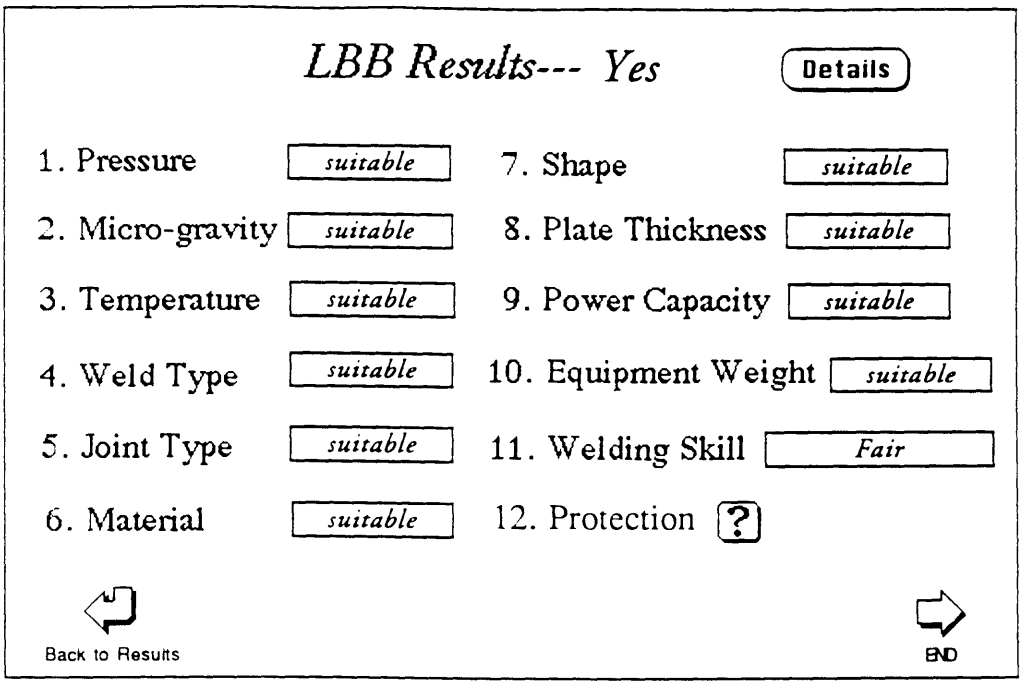

RW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
not_availabl
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Well_Done
Back to Results
END

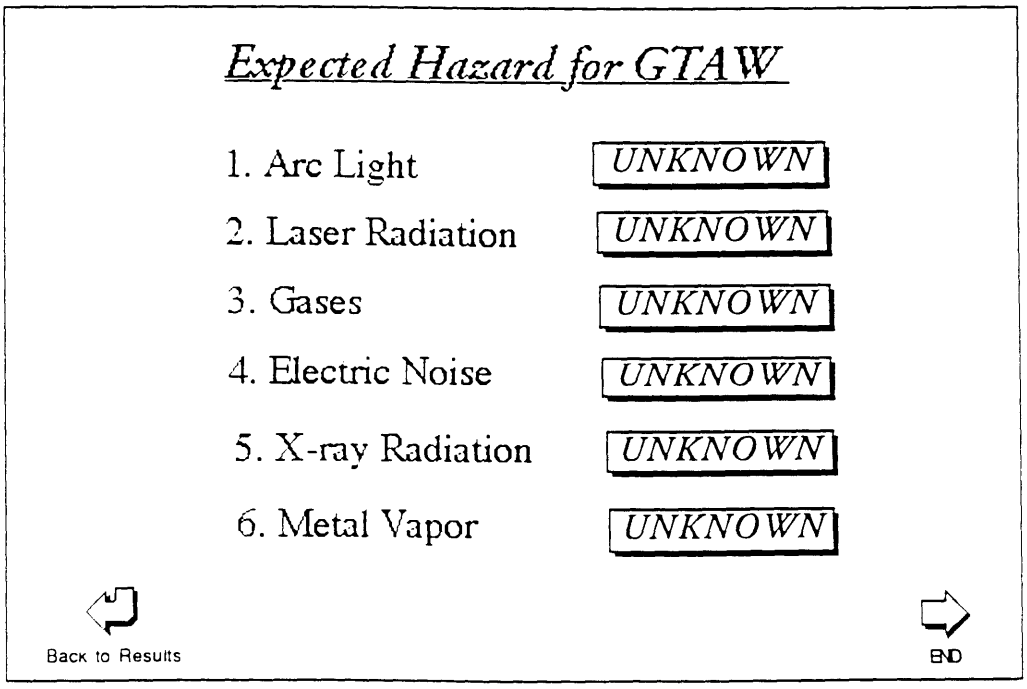

FW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
not_availabl
8. Plate Thickness
suitable
9. Power Capacity
not_availabl
10. Equipment Weight
too_heavy
11. Welding Skill
Well_Done
Back to Results
END
SW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
not_availabl
6. Material
suitable
7. Shape
not_availabl
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
too_heavy
11. Welding Skill
Well_Done
Back to Results
END

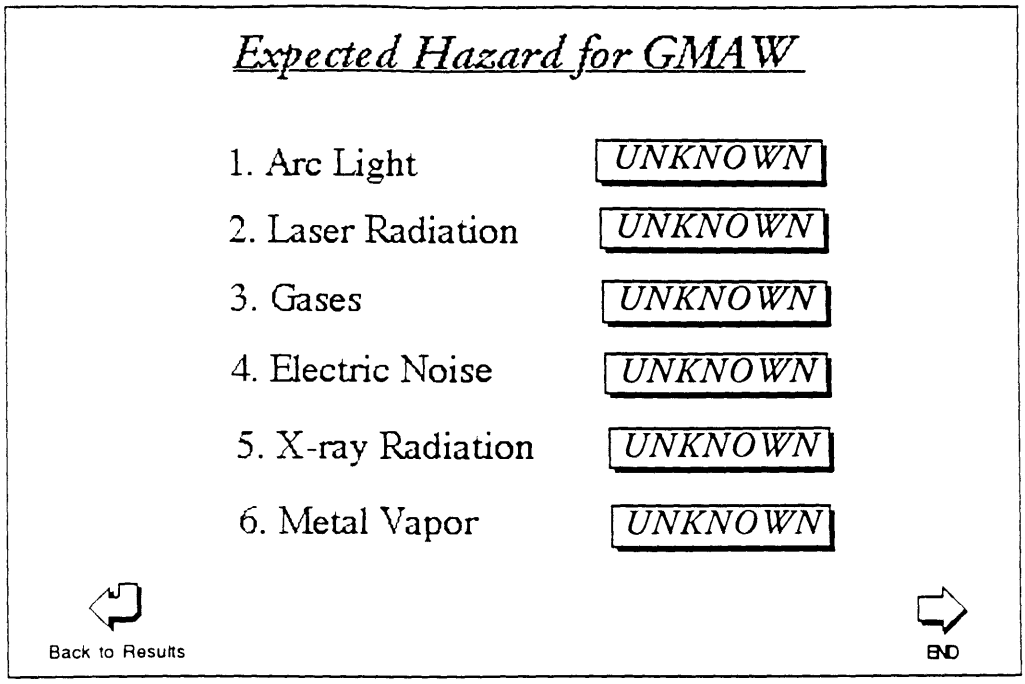

TW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
available
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
not_availabl
10. Equipment Weight
too_heavy
11. Welding Skill
Well_Done
Back to Results
END
GTAB Results--- No
Details
1. Pressure
not_availabl
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
too_heavy
11. Welding Skill
Fair
Back to Results
END

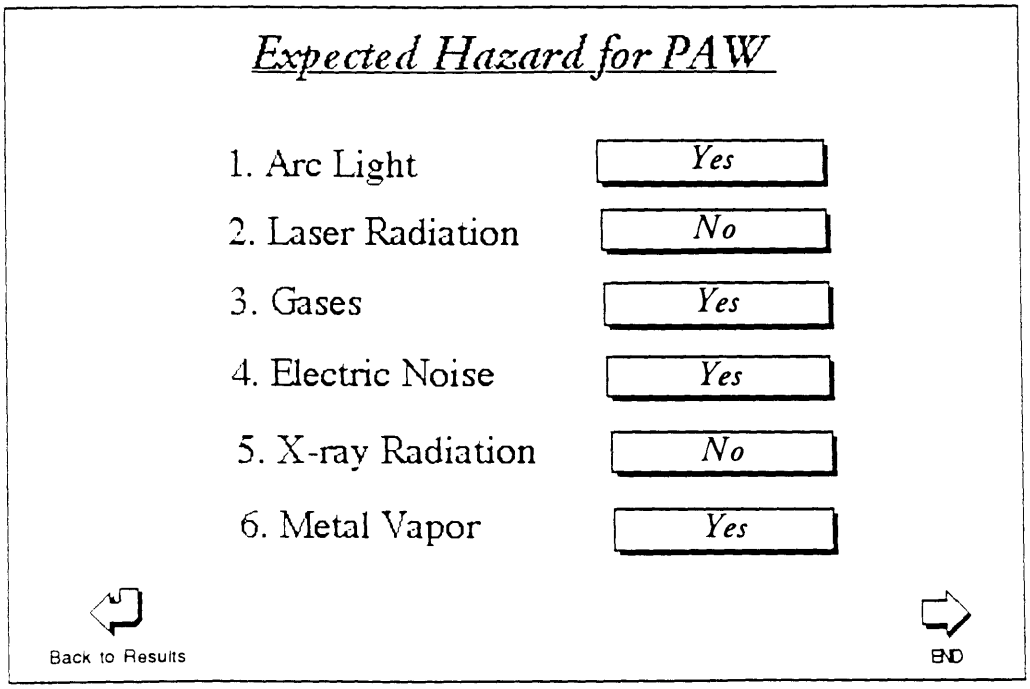

GMAB Results--- No
Details
1. Pressure
not_availabl
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
Back to Results
END

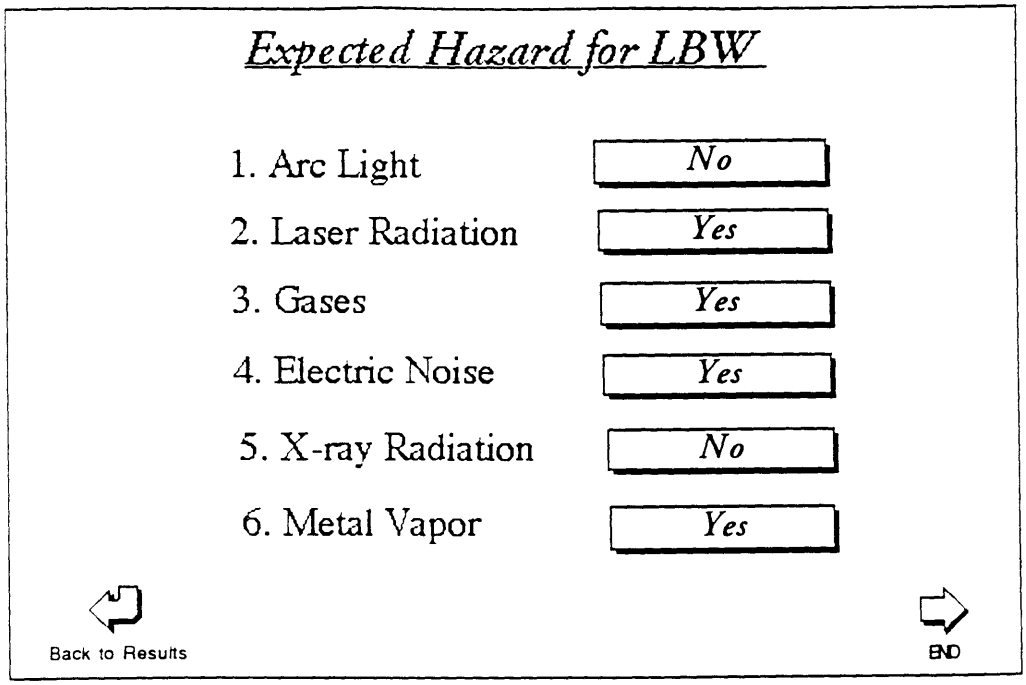

EBB Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

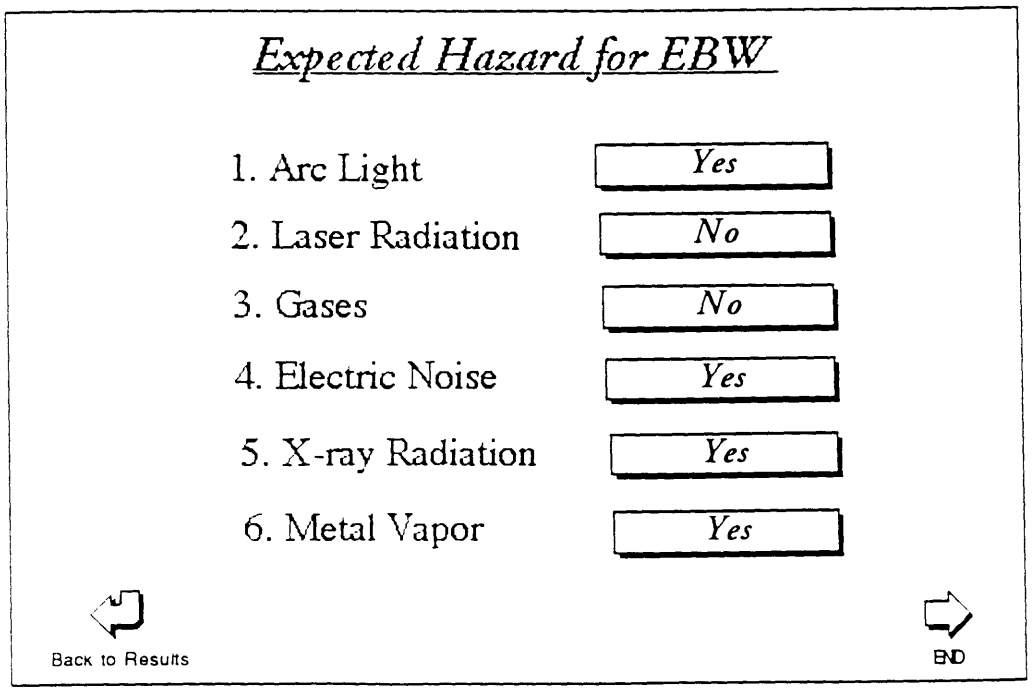

LBB Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

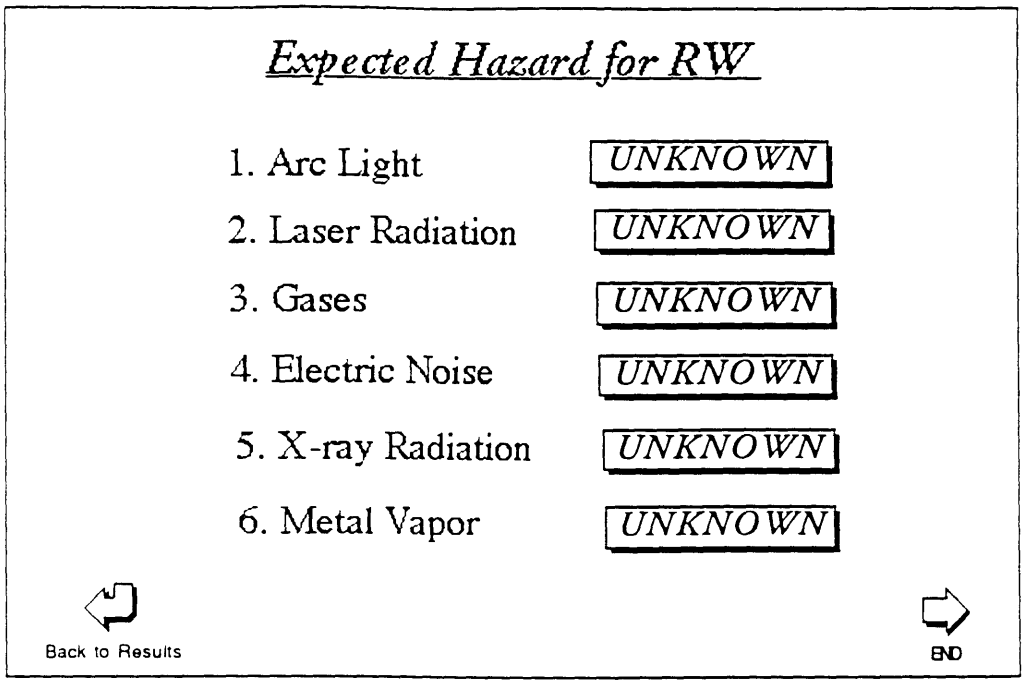

Expected Hazard for GTAW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

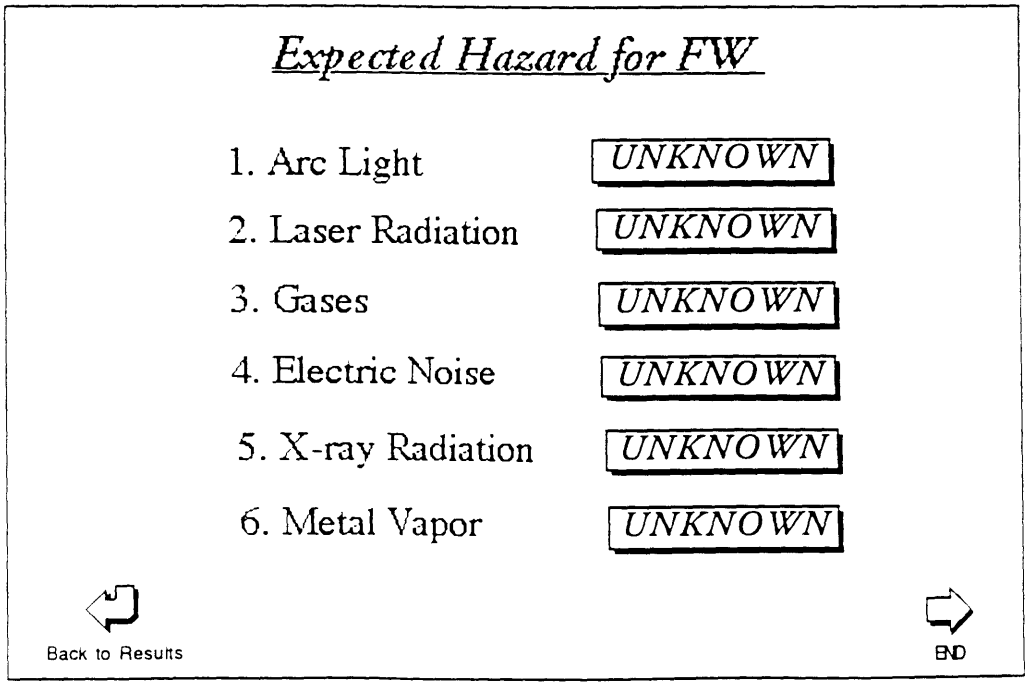

Expected Hazard for GMAW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

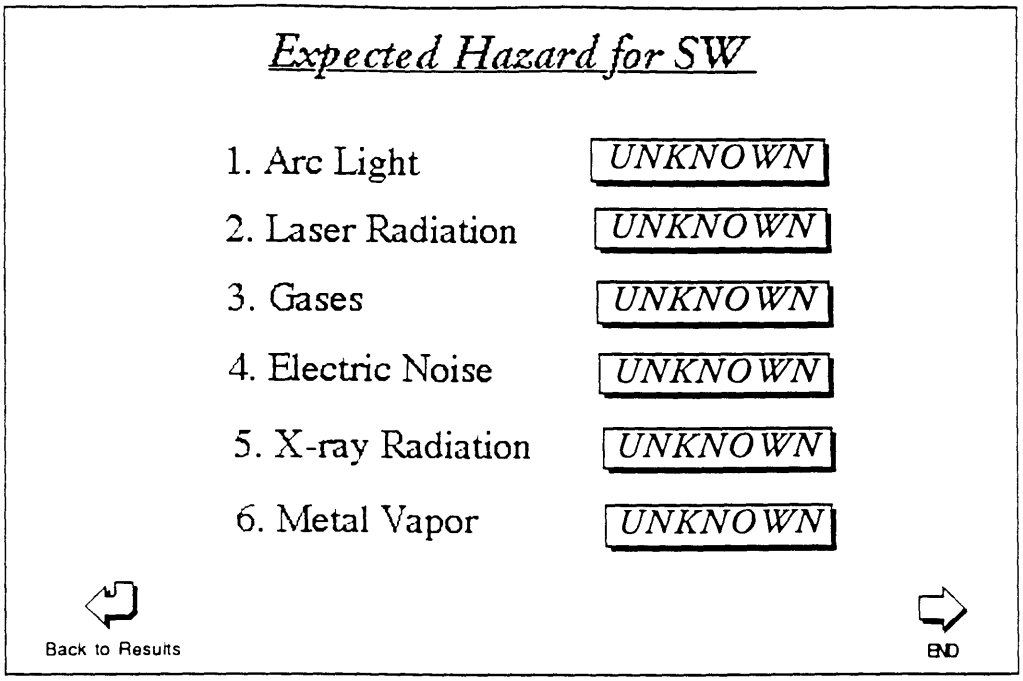

Expected Hazard for PAW
1. Arc Light
Yes
2. Laser Radiation
No
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

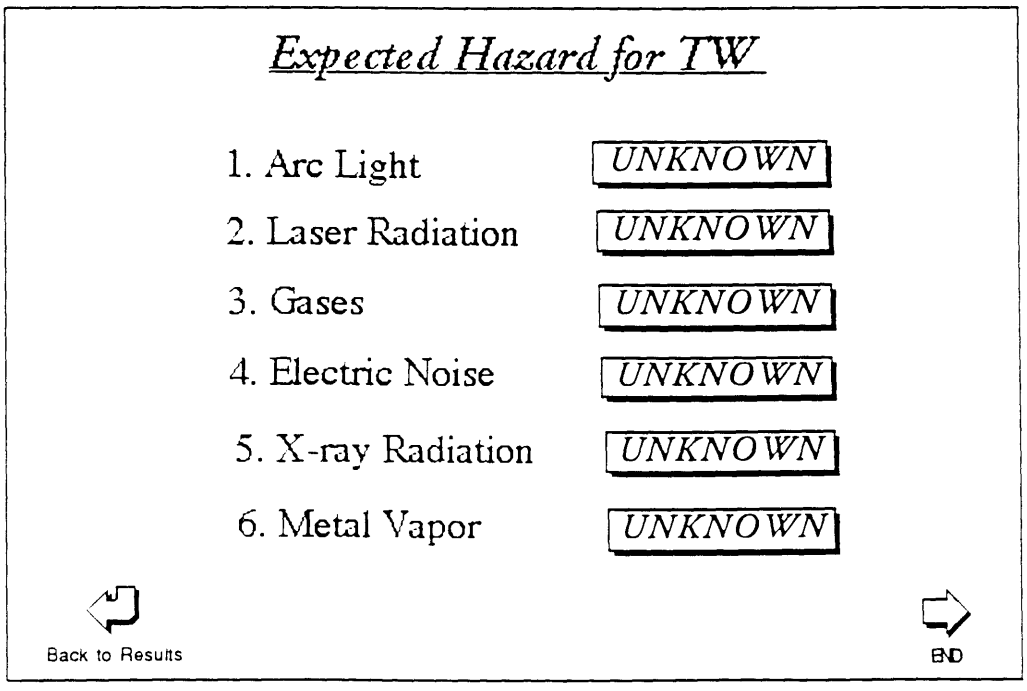

Expected Hazard for LBW
1. Arc Light
No
2. Laser Radiation
Yes
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

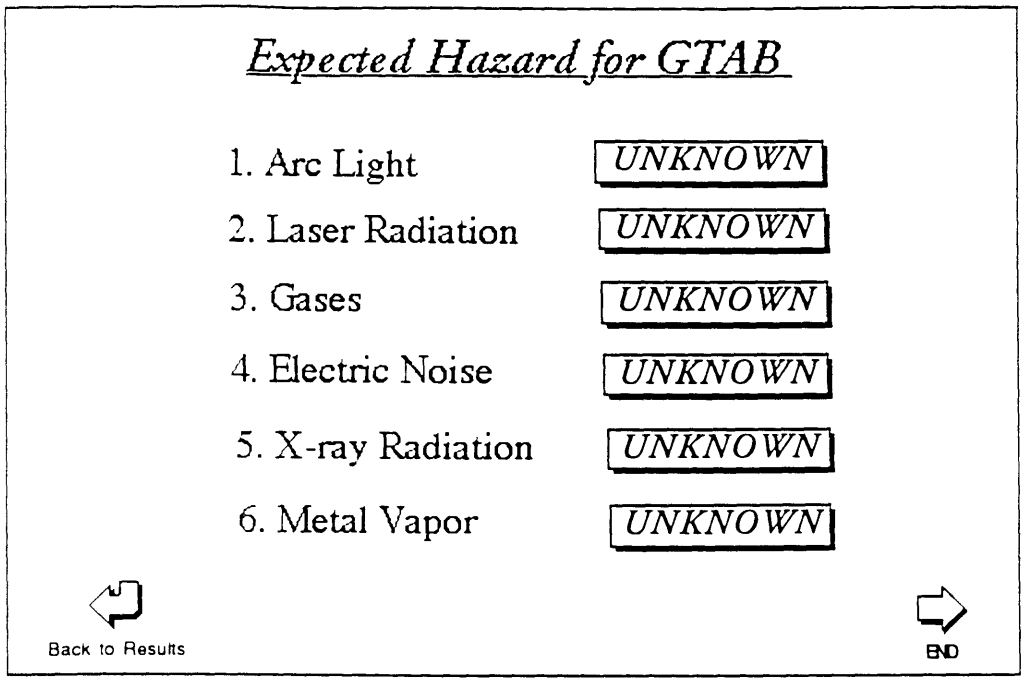

Expected Hazard for EBW
1. Arc Light
Yes
2. Laser Radiation
No
3. Gases
No
4. Electric Noise
Yes
5. X-ray Radiation
Yes
6. Metal Vapor
Yes
Back to Results
END

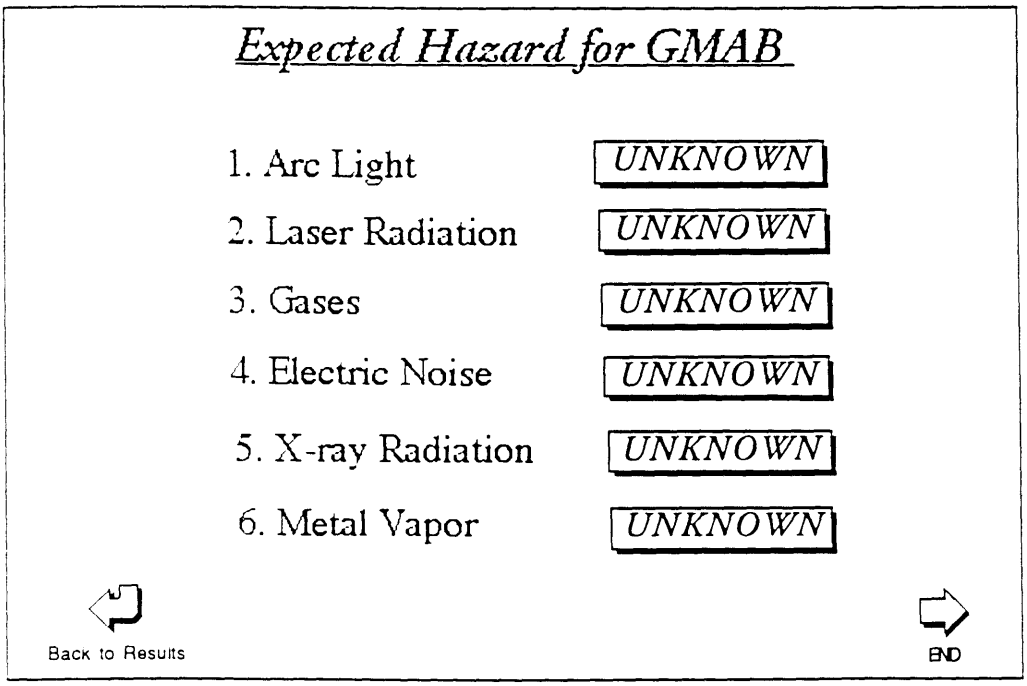

Expected Hazard for RW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

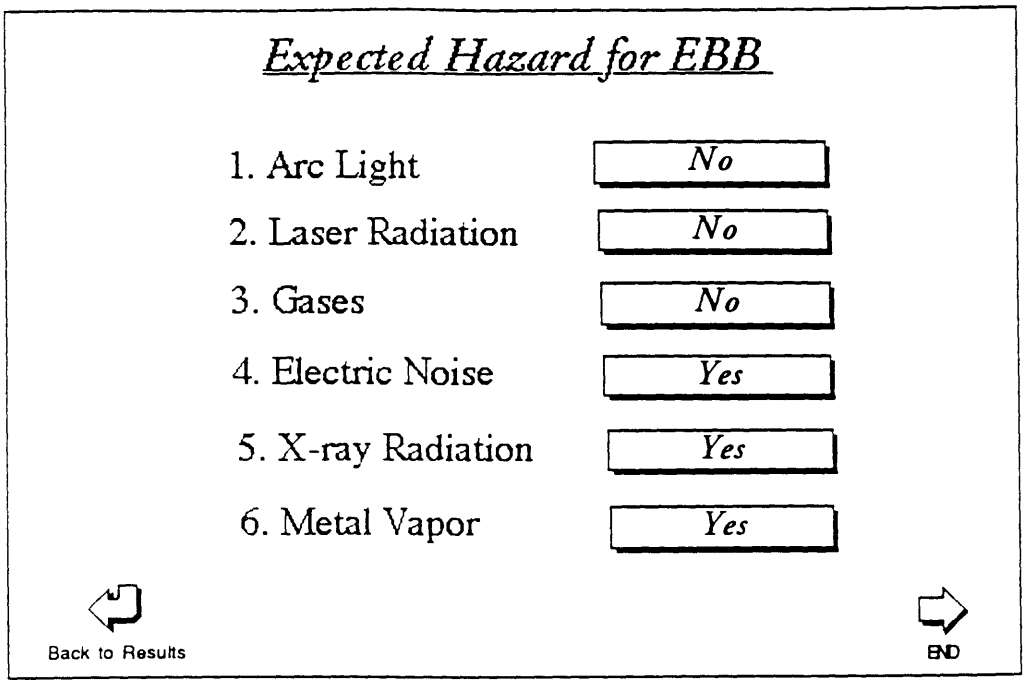

Expected Hazard for FW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

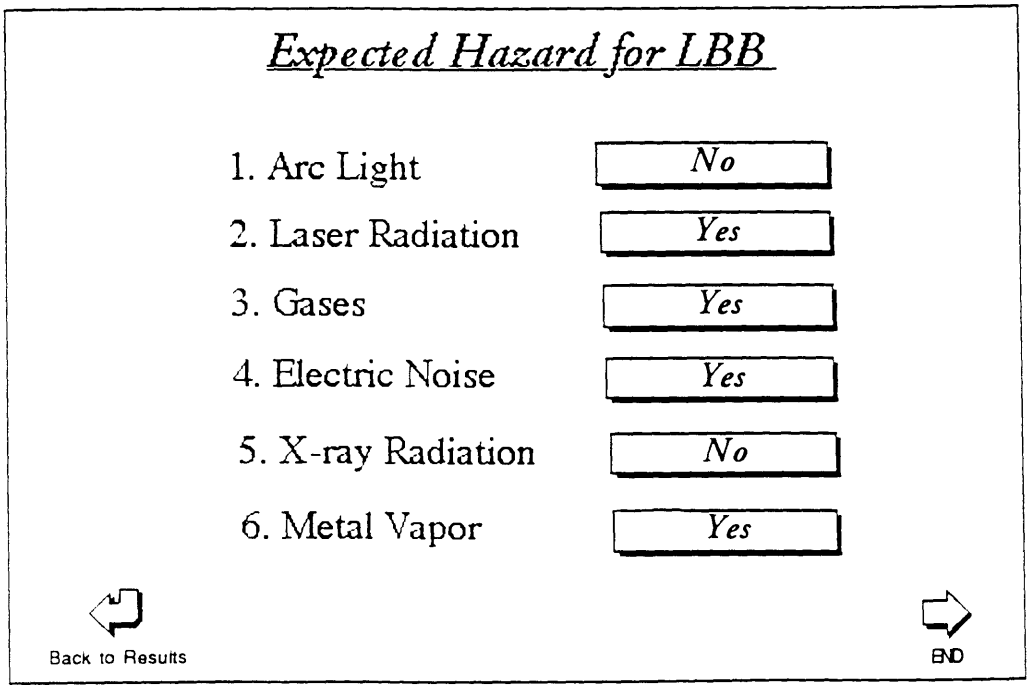

Expected Hazard for SW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for TW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for GTAB
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for GMAB
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for EBB
1. Arc Light
No
2. Laser Radiation
No
3. Gases
No
4. Electric Noise
Yes
5. X-ray Radiation
Yes
6. Metal Vapor
Yes
Back to Results
END


Expected Hazard for LBB
1. Arc Light
No
2. Laser Radiation
Yes
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

8.2 Repair of Inner Shell of Space Vehicle

There may be a case in which the inner shape is broken and need to be repaired. In this case the following situation is assumed.

Objective

An astronaut repairs the break on the inner shell of the space station under the instruction of experts on Earth.

Location

Inside the space station on the orbit of Earth

Environmental Conditions

Pressure: 0.8 ATM

Gravity: 0.0 G

Temperature: 300 °K

Mission Requirements

Weld type: Fillet (F)

Joint type: Lap joint

Material: Aluminum

Joint shape: Plate-Plate joint

Workpiece thickness: 2 mm

Allowed power capacity: 50 kW

Allowed equipment weight: 100 kg

Operator: Astronaut with expert help

The results calculated by the system are as follows:

1. GTAW: Not feasible

   Reasons: too heavy equipment weight

2. GMAW: Feasible

   Hazard: arc light, gases, electric noise, metal vapor

3. PAW: Feasible

   Hazard: arc light, gases, electric noise, metal vapor

4. LBW: Feasible

   Hazard: laser radiation, gases, electric noise, metal vapor

5. EBW: Not feasible

   Reasons: no vacuum condition

6. RW: Feasible

   Hazard: electric noise

7. FW: Not feasible

Reasons: unavailable joint type, joint shape and power capacity
too heavy equipment weight

8. SW: Not feasible

Reasons: unavailable joint type, joint shape
too heavy equipment weight

9. TW: Not feasible

Reasons: unavailable joint type and power capacity
too heavy equipment weight

10. GTAB: Not feasible

Reasons: too heavy equipment weight

11. GMAB: Feasible

Hazard: arc light, gases, electric noise, metal vapor

12. EBB: Not feasible

Reasons: no vacuum condition

13. LBB: Feasible

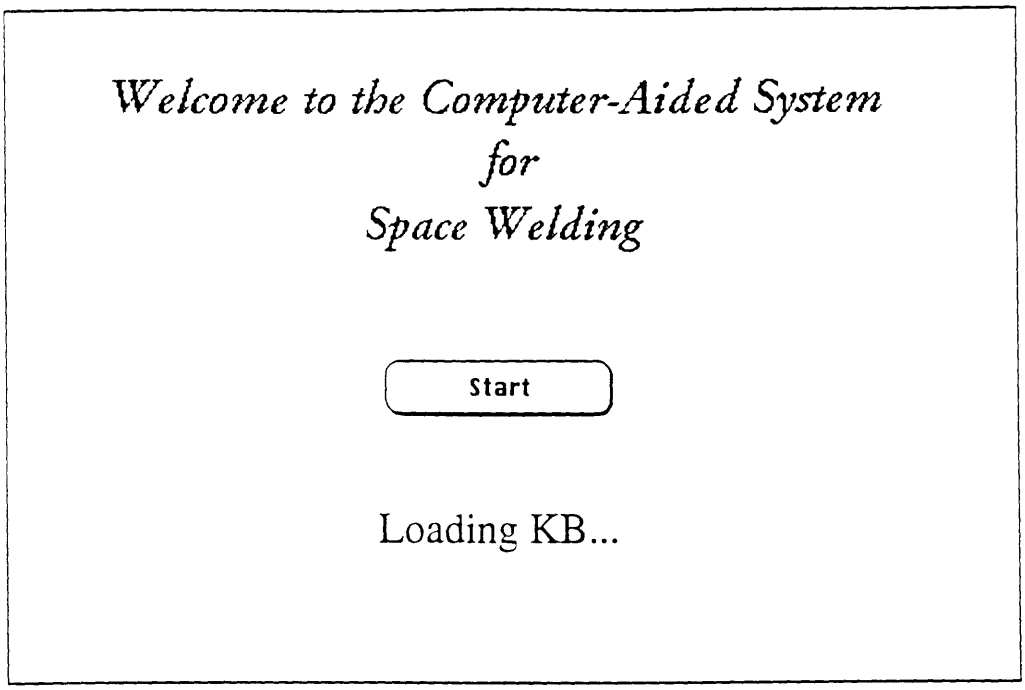
Hazard: laser radiation, gases, electric noise, metal vapor

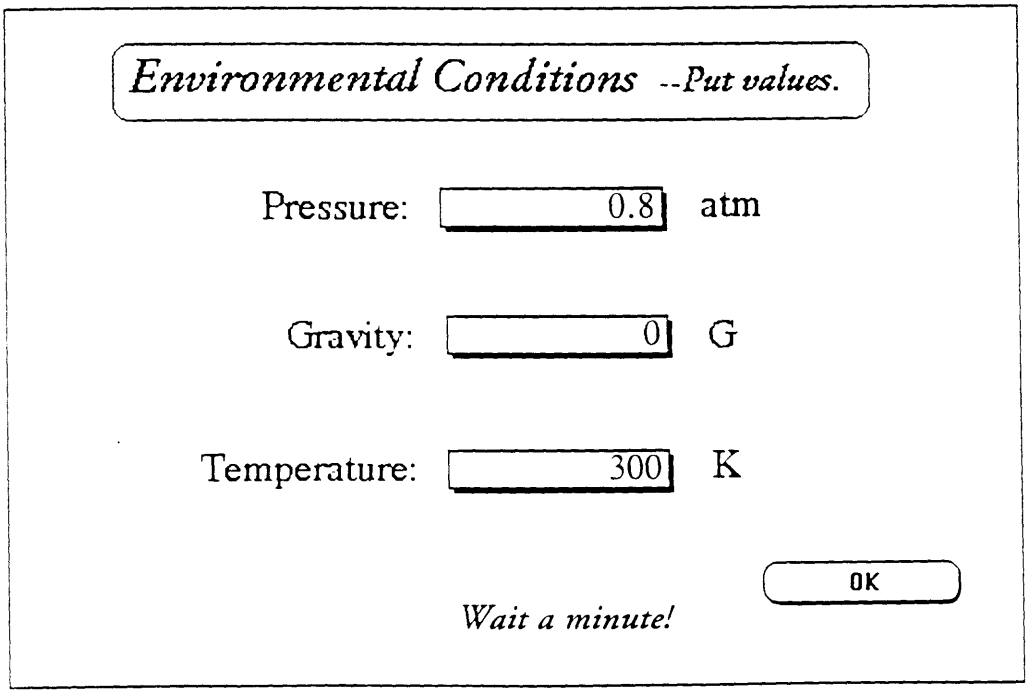
Under the assumed conditions, EBW is not feasible, because of the no vacuum condition in the space station. If this reason is eliminated by improving EBW process possibly using a portable vacuum chamber, EBW

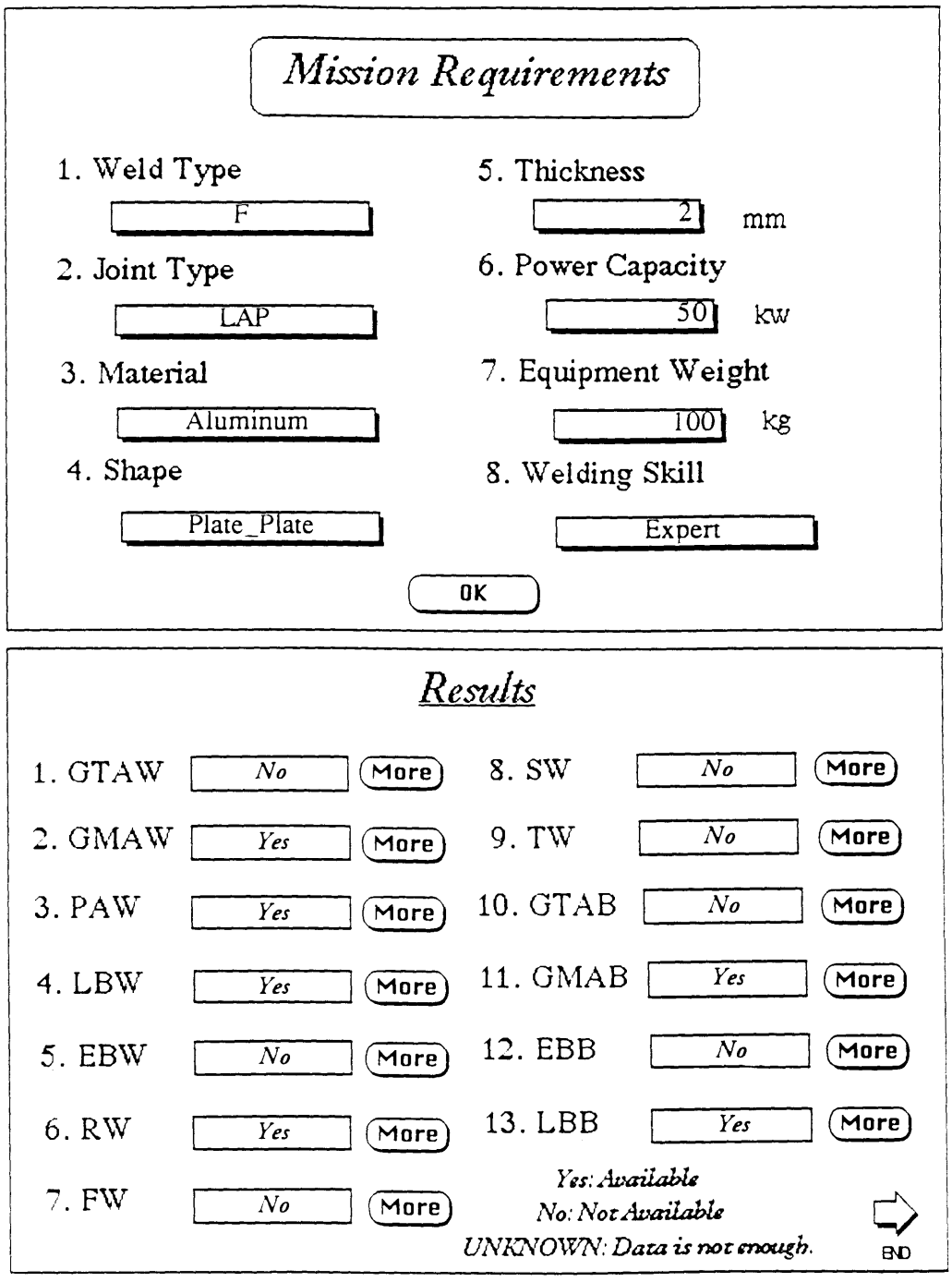
will have great possibility to be a main fabrication process in the future. Therefore, we can say that the most promising area to improve this specific joining process is to find a way to use EBW under no vacuum condition.

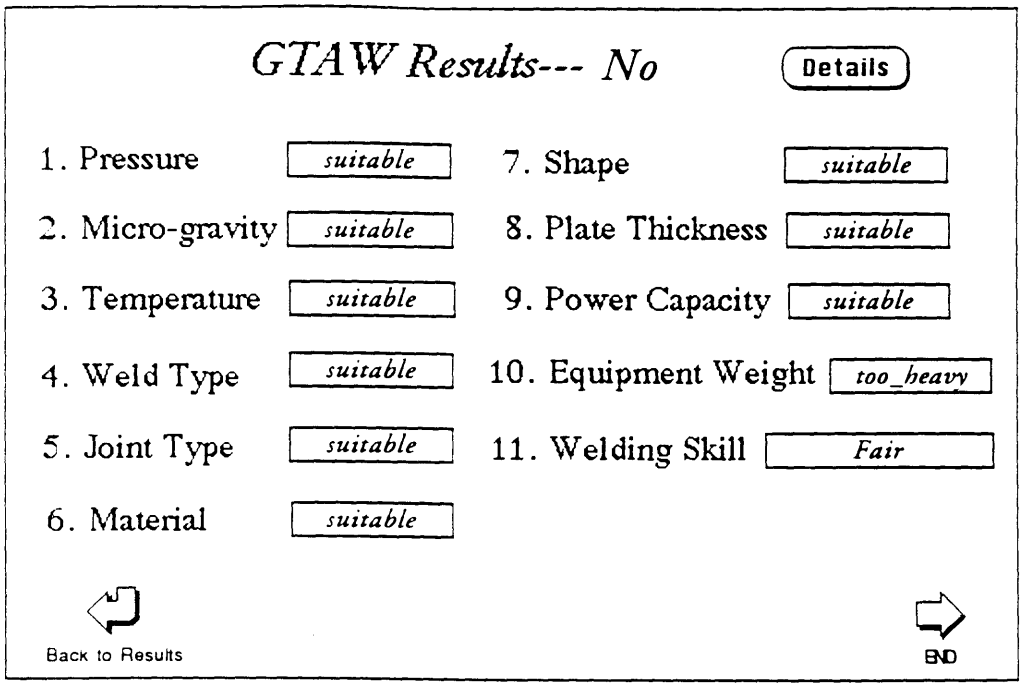
For other processes the system can study the feasibility of each process and tell the most promising areas of future research or the expected hazards.

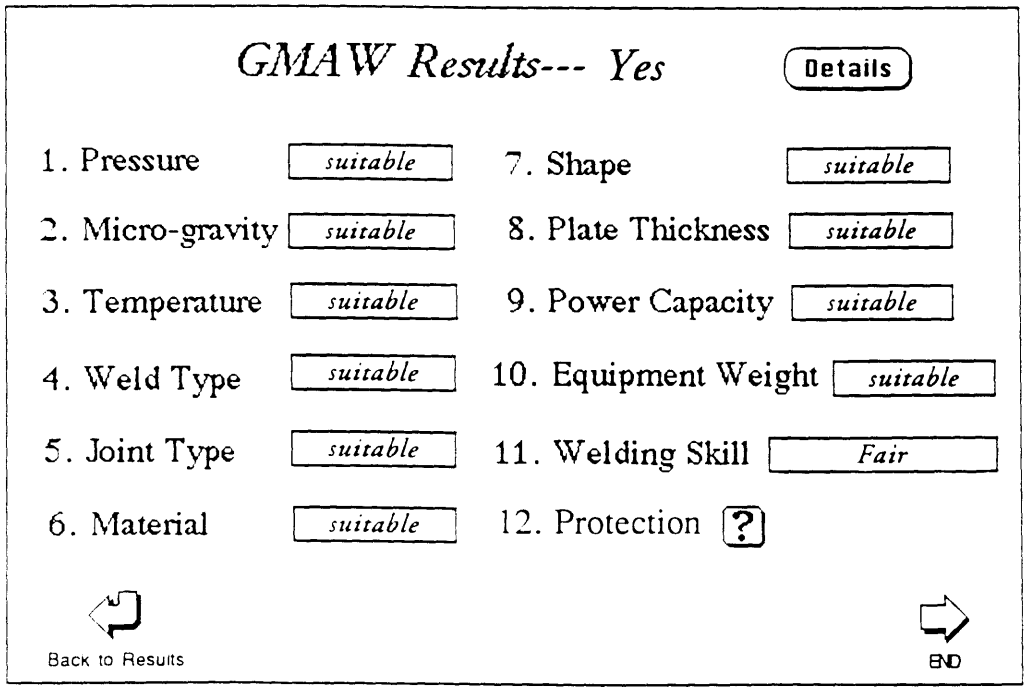
The user interface with which the system conducted feasibility study is shown from the next page.

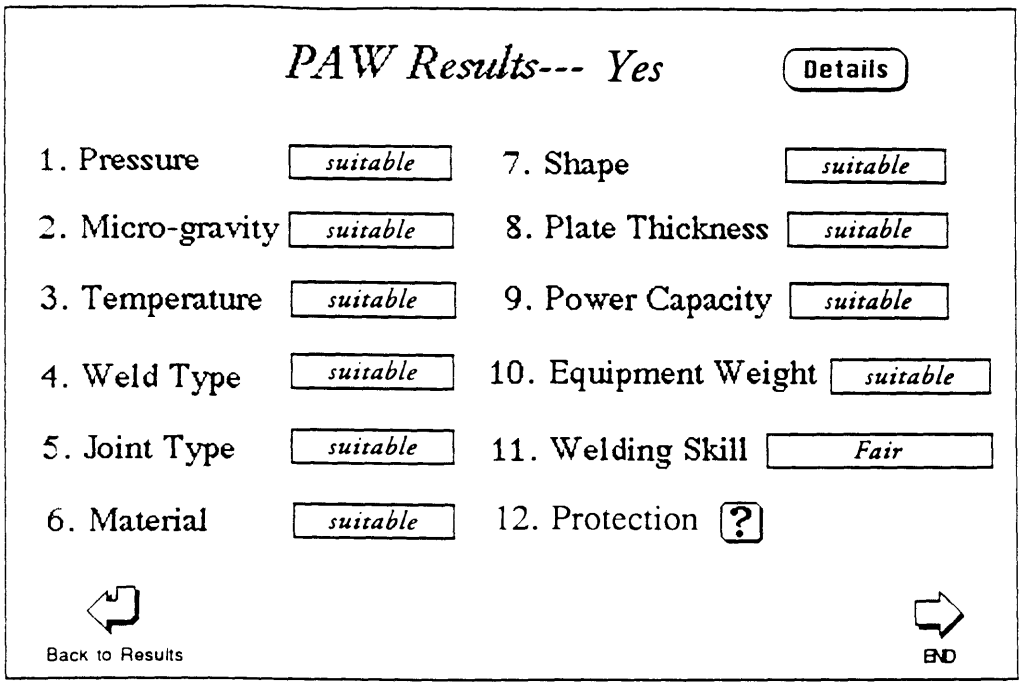

Welcome to the Computer-Aided System
for
Space Welding
Start
Loading KB...

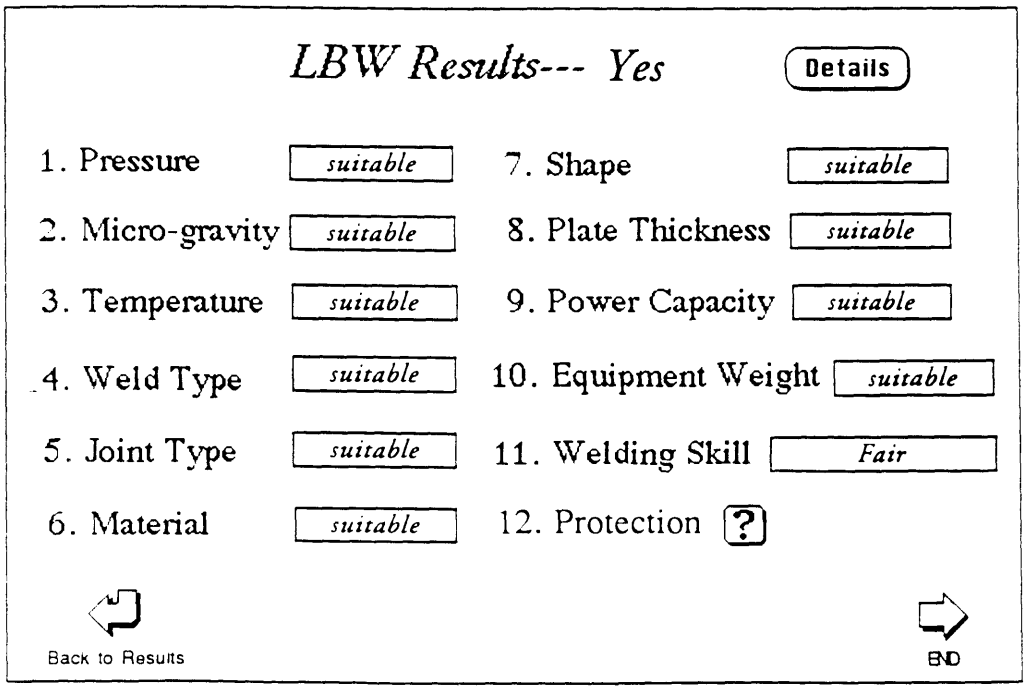

Environmental Conditions --Put values.
Pressure: 0.8 atm
Gravity: 0 G
Temperature: 300 K
OK
Wait a minute!

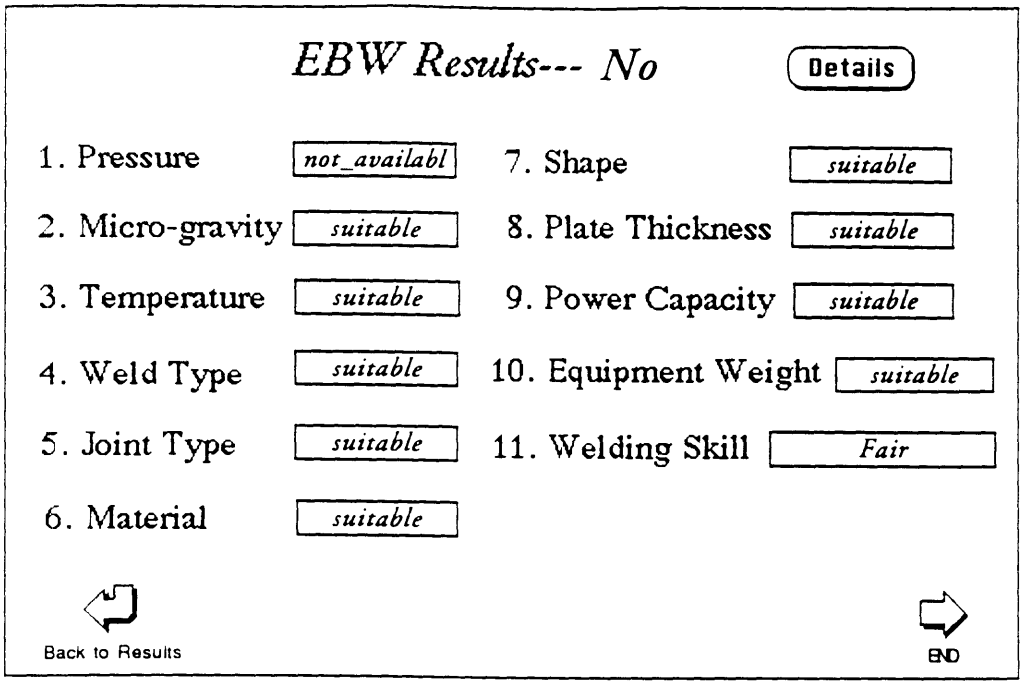

Mission Requirements
1. Weld Type
F
2. Joint Type
LAP
3. Material
Aluminum
4. Shape
Plate_Plate
5. Thickness
2
mm
6. Power Capacity
50
kw
7. Equipment Weight
100
kg
8. Welding Skill
Expert
OK
Results
1. GTAW
No
More
2. GMAW
Yes
More
3. PAW
Yes
More
4. LBW
Yes
More
5. EBW
No
More
6. RW
Yes
More
7. FW
No
More
8. SW
No
More
9. TW
No
More
10. GTAB
No
More
11. GMAB
Yes
More
12. EBB
No
More
13. LBB
Yes
More
Yes: Available
No: Not Available
UNKNOWN: Data is not enough.
END

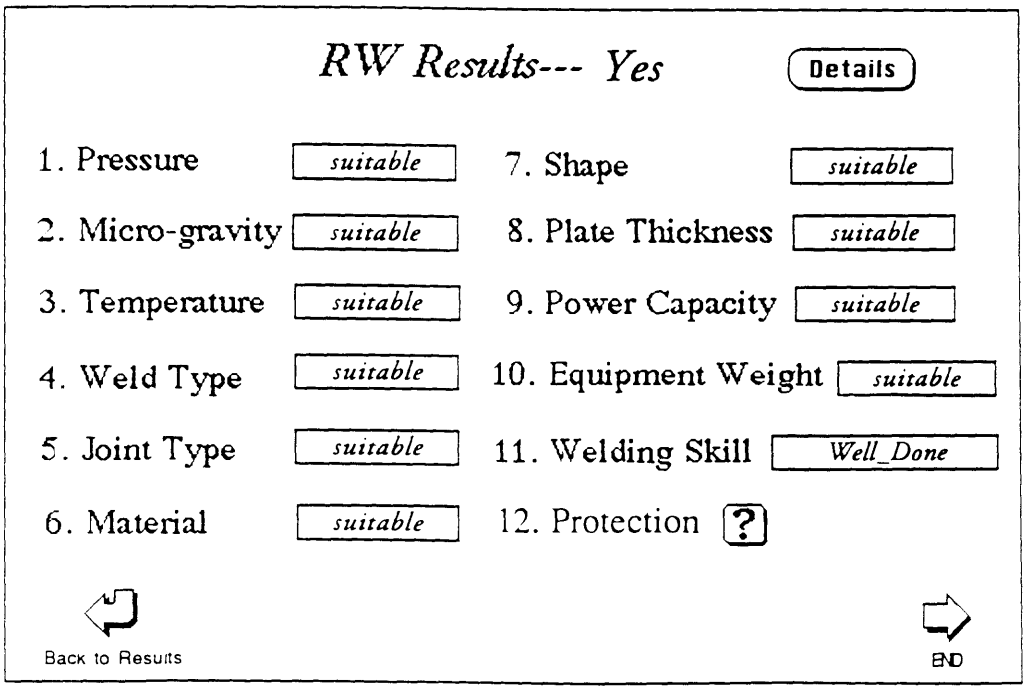

GTAW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
too_heavy
11. Welding Skill
Fair
Back to Results
END

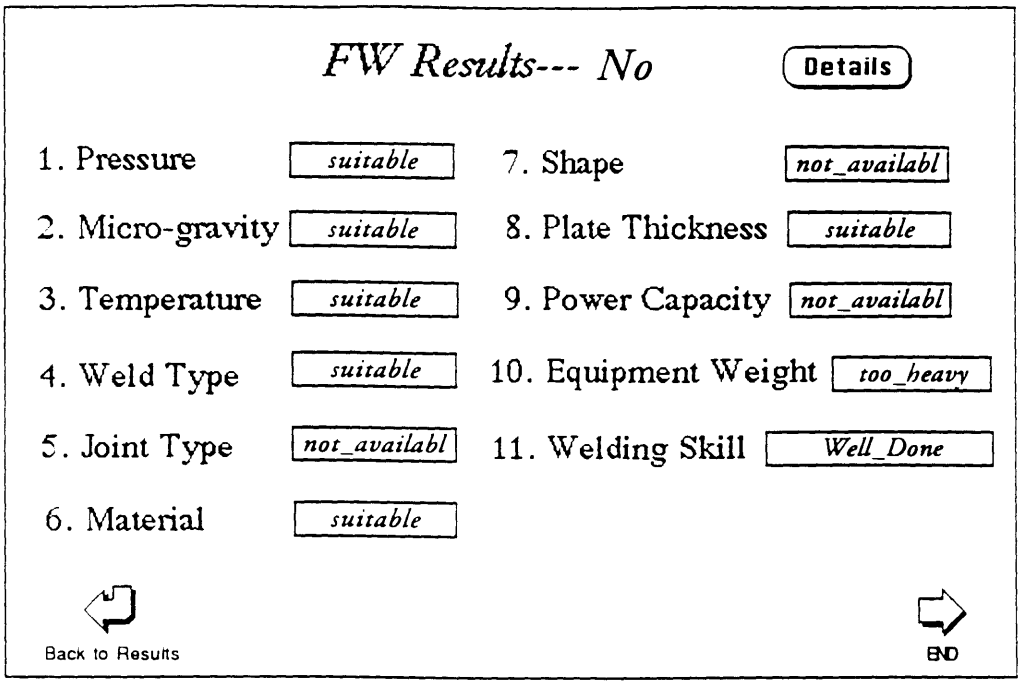

GMAW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

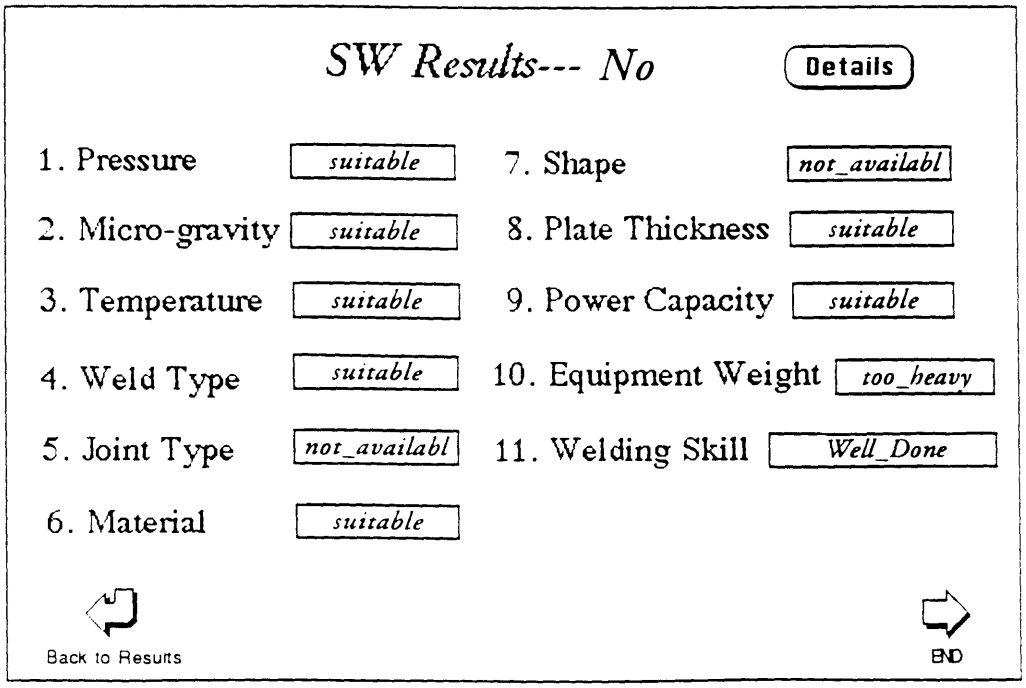

PAW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

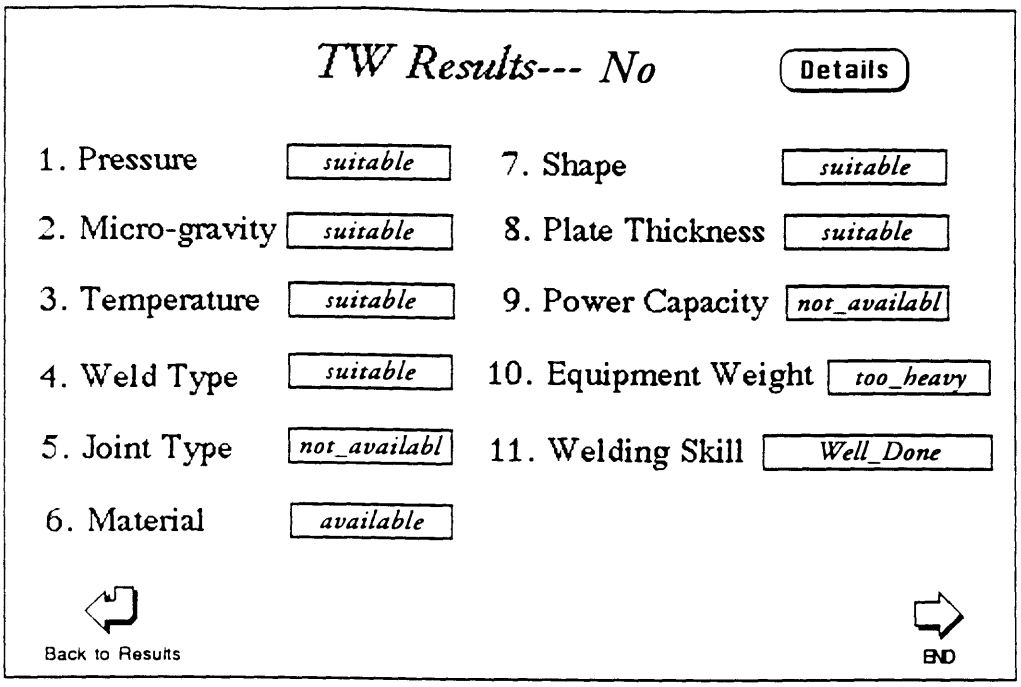

LBW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

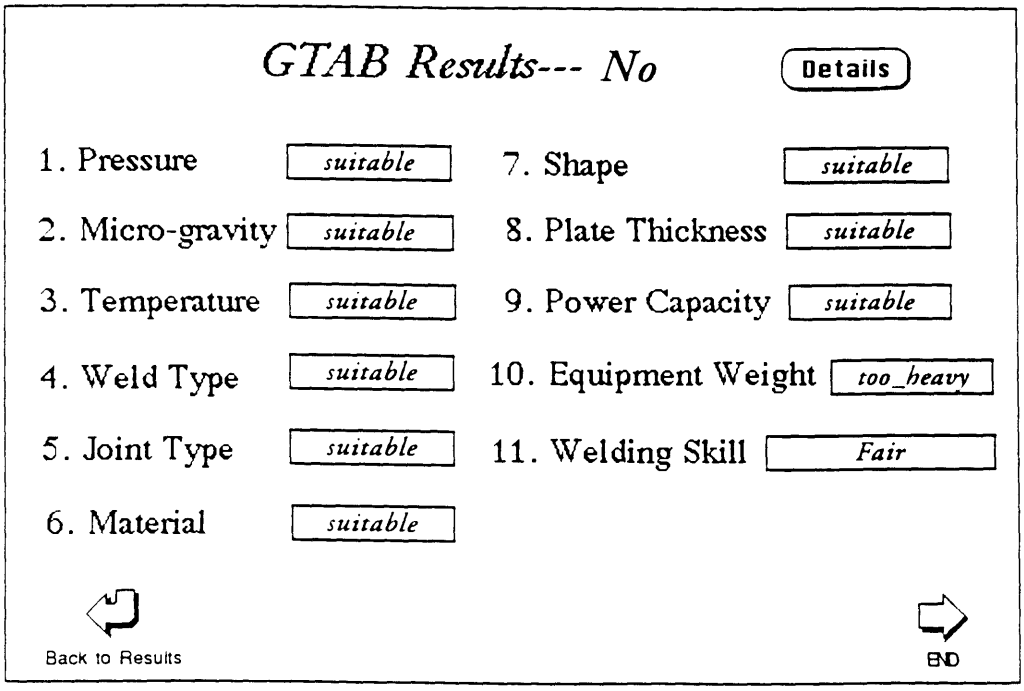

EBW Results--- No
Details
1. Pressure
not_availabl
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
Back to Results
END

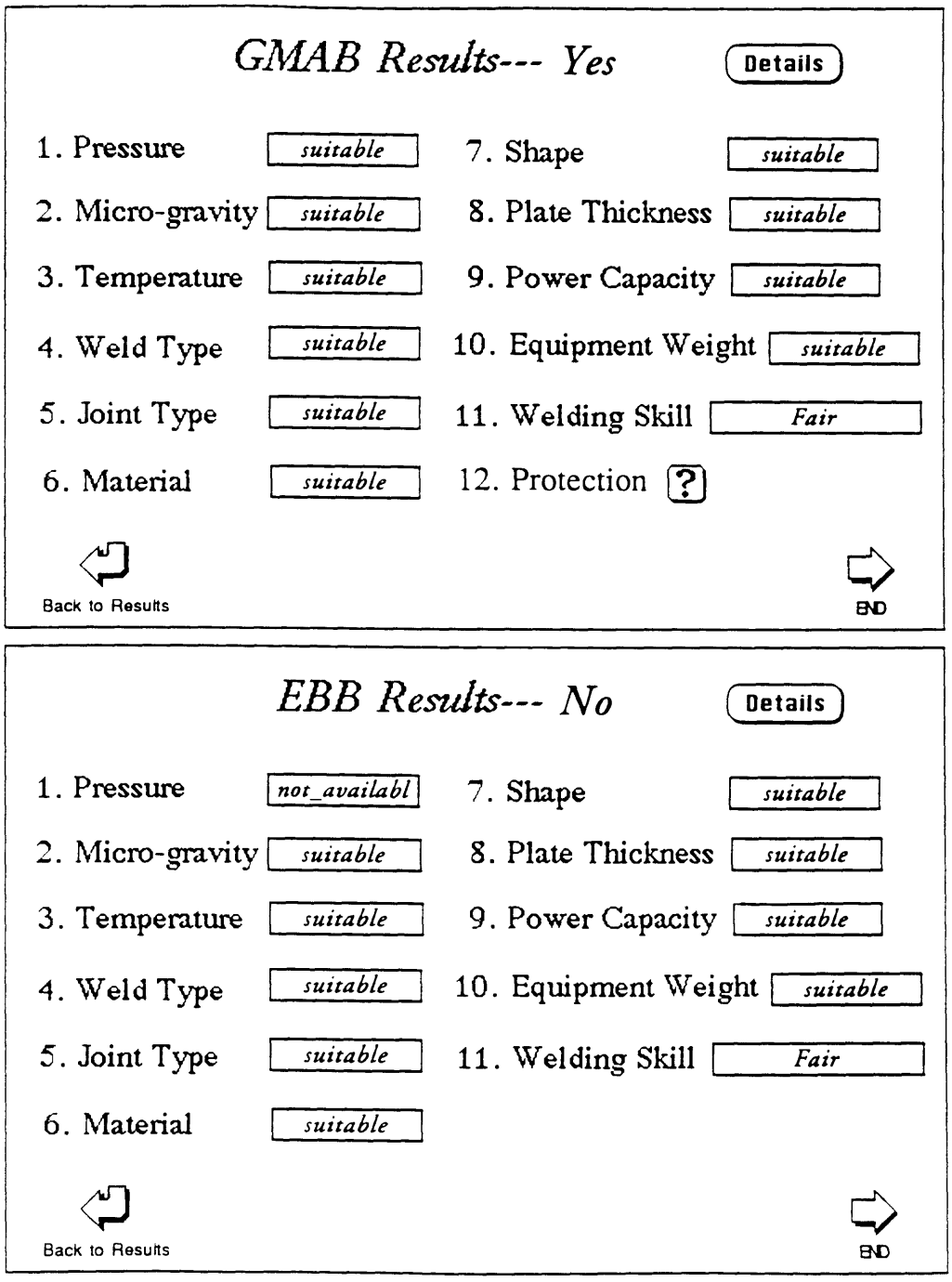

RW Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Well_Done
12. Protection
?
Back to Results
END

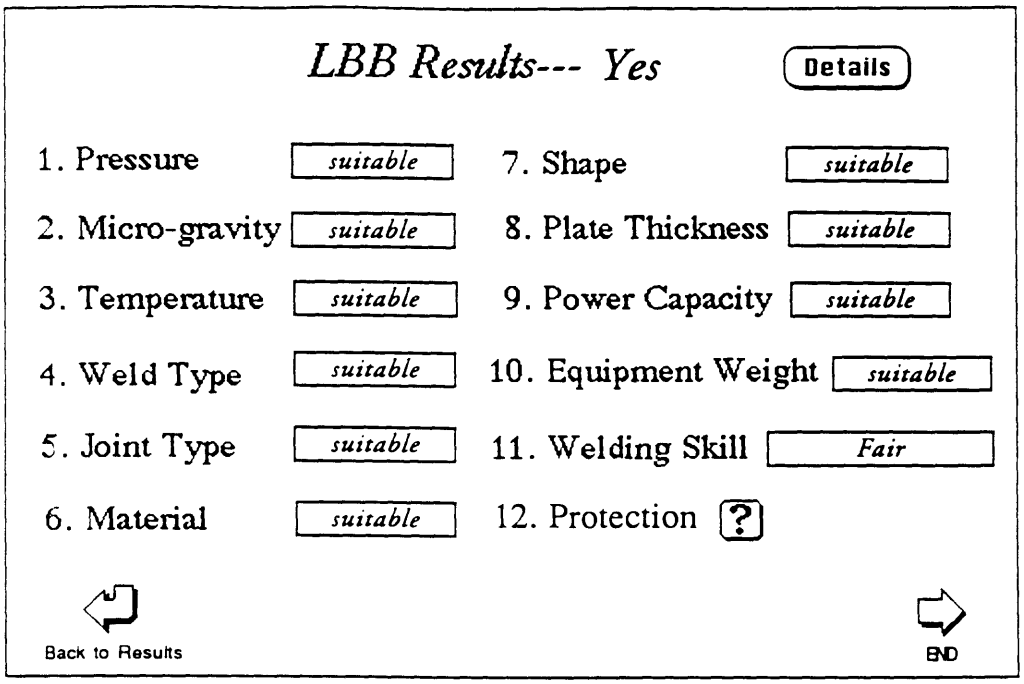

FW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
not_availabl
6. Material
suitable
7. Shape
not_availabl
8. Plate Thickness
suitable
9. Power Capacity
not_availabl
10. Equipment Weight
too_heavy
11. Welding Skill
Well_Done
Back to Results
END

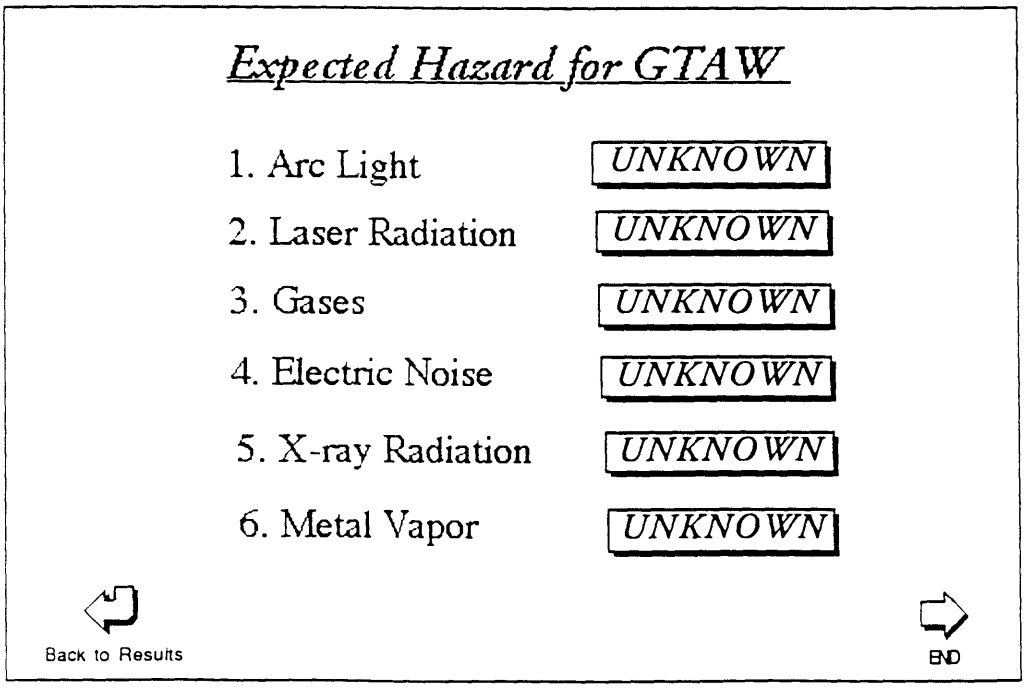

SW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
not_availabl
6. Material
suitable
7. Shape
not_availabl
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
too_heavy
11. Welding Skill
Well_Done
Back to Results
END

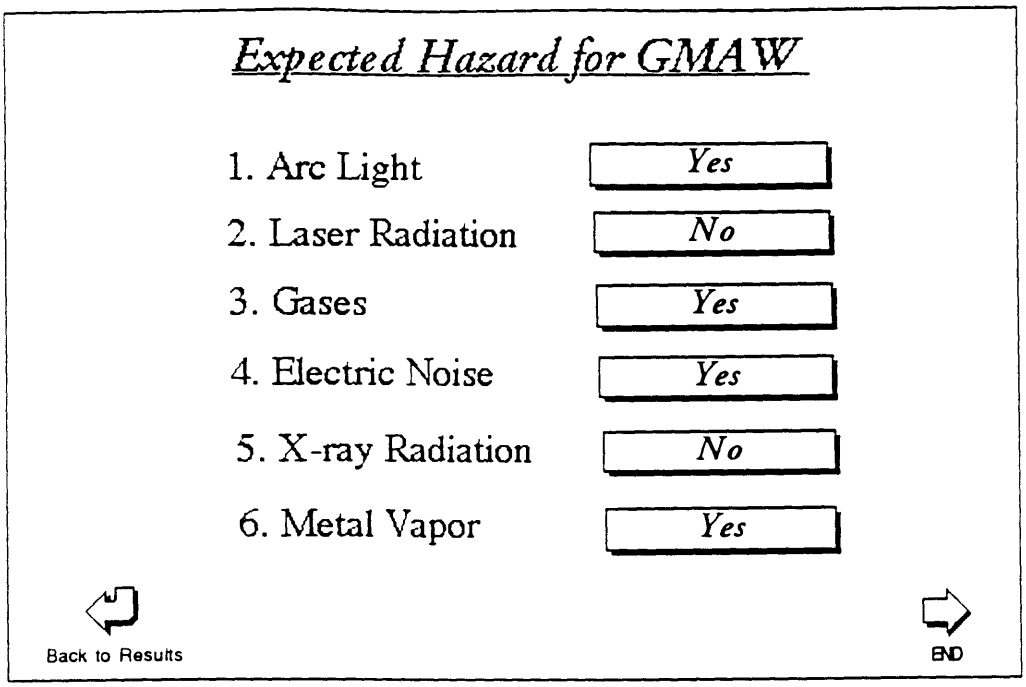

TW Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
not_availabl
6. Material
available
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
not_availabl
10. Equipment Weight
too_heavy
11. Welding Skill
Well_Done
Back to Results
END

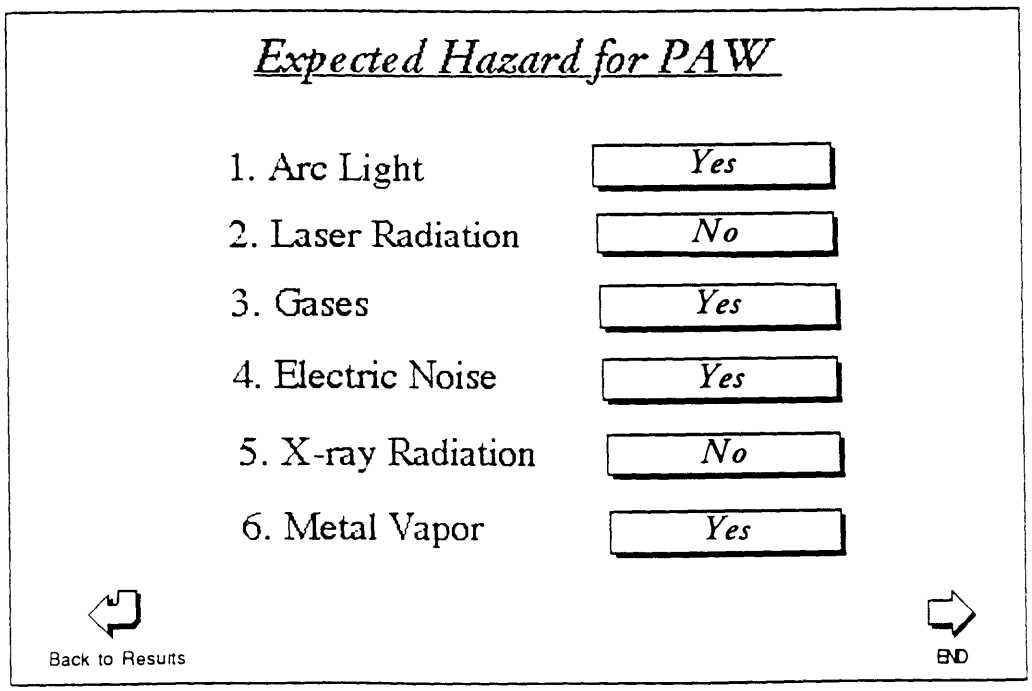

GTAB Results--- No
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
too_heavy
11. Welding Skill
Fair
Back to Results
END

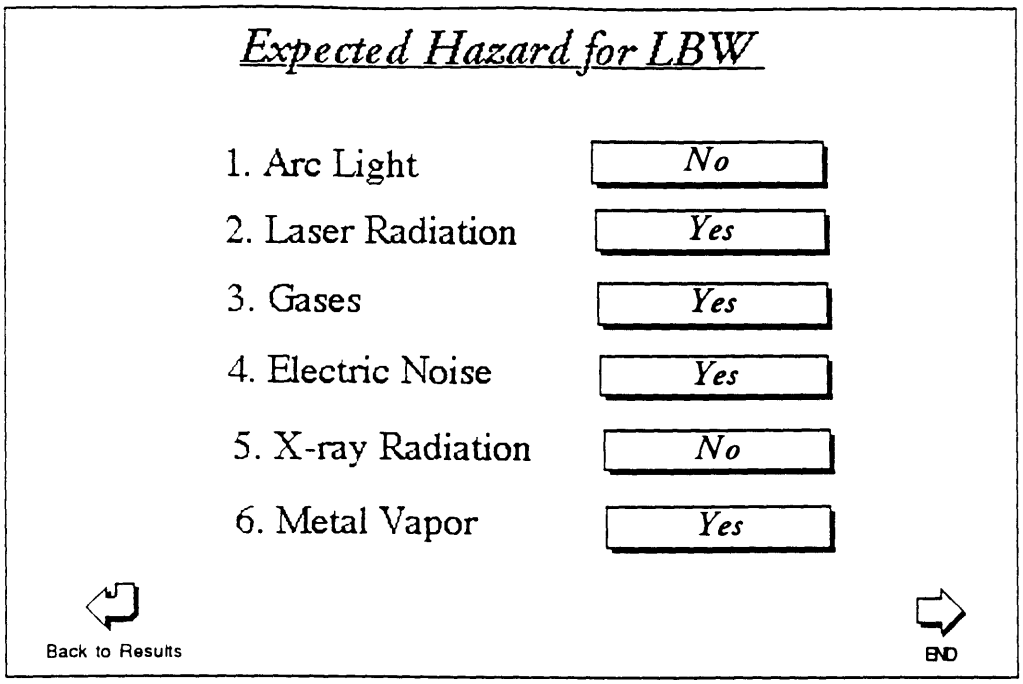

GMAB Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END
EBB Results--- No
Details
1. Pressure
not_availabl
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
Back to Results
END

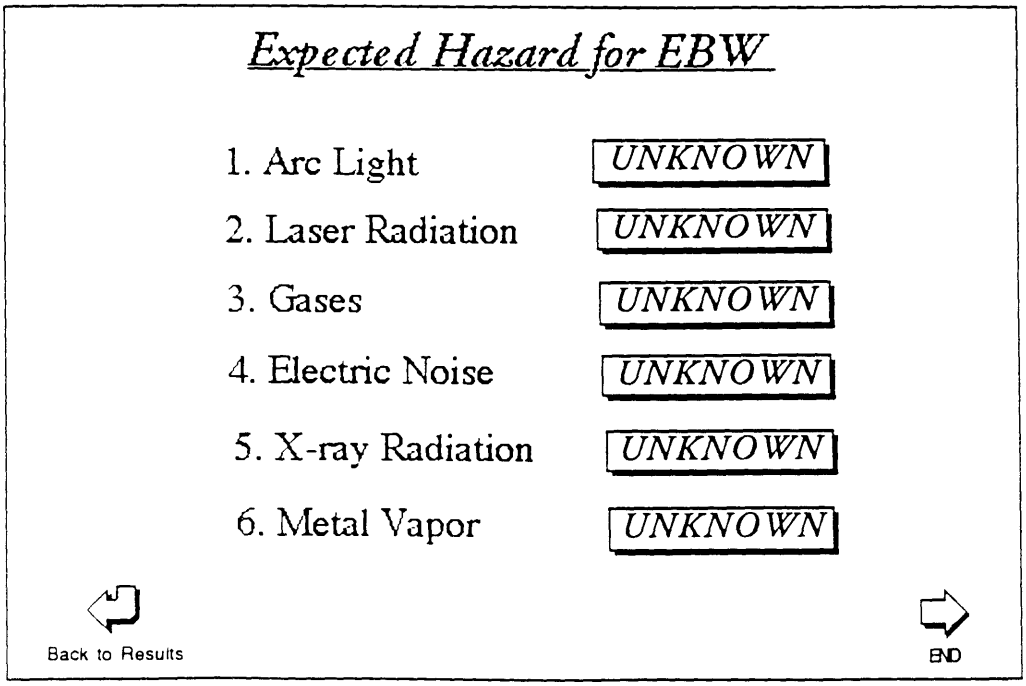

LBB Results--- Yes
Details
1. Pressure
suitable
2. Micro-gravity
suitable
3. Temperature
suitable
4. Weld Type
suitable
5. Joint Type
suitable
6. Material
suitable
7. Shape
suitable
8. Plate Thickness
suitable
9. Power Capacity
suitable
10. Equipment Weight
suitable
11. Welding Skill
Fair
12. Protection
?
Back to Results
END

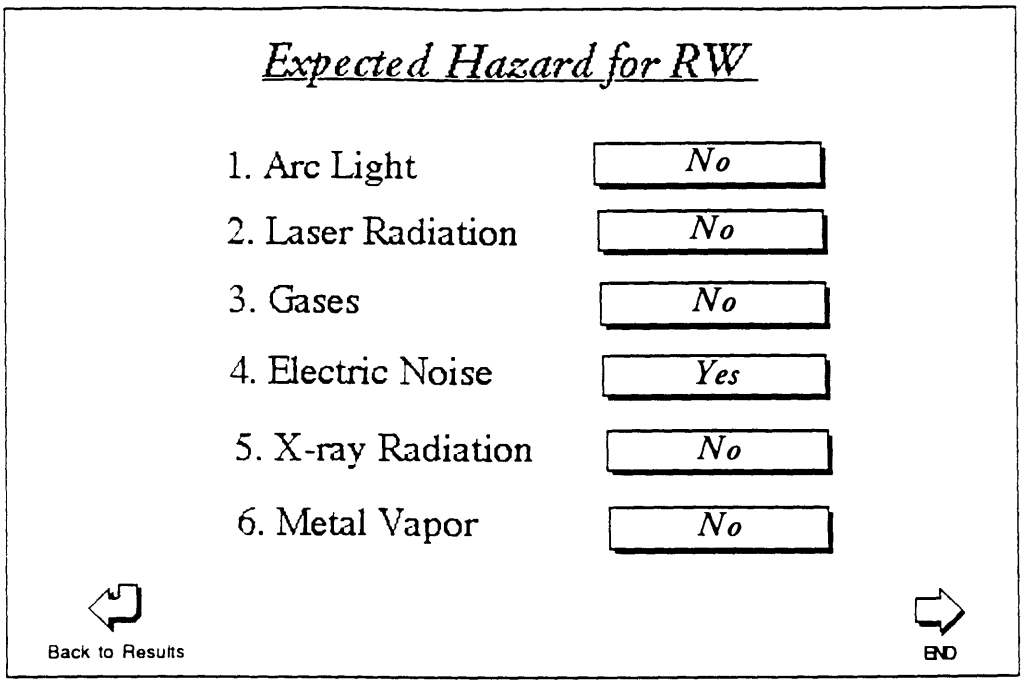

Expected Hazard for GTAW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

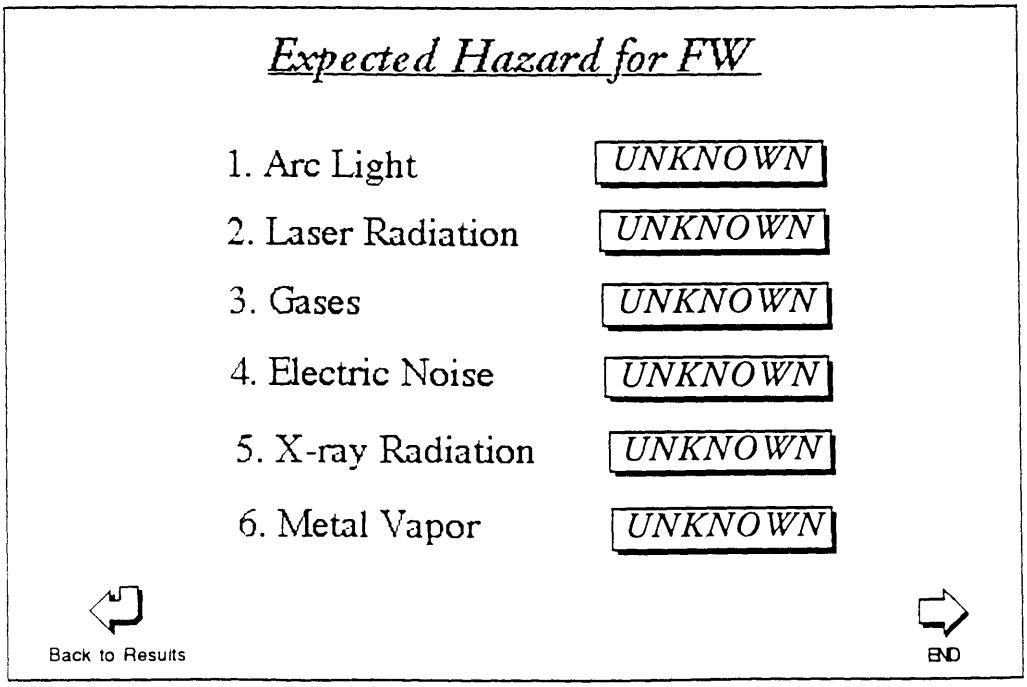

Expected Hazard for GMAW
1. Arc Light
Yes
2. Laser Radiation
No
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

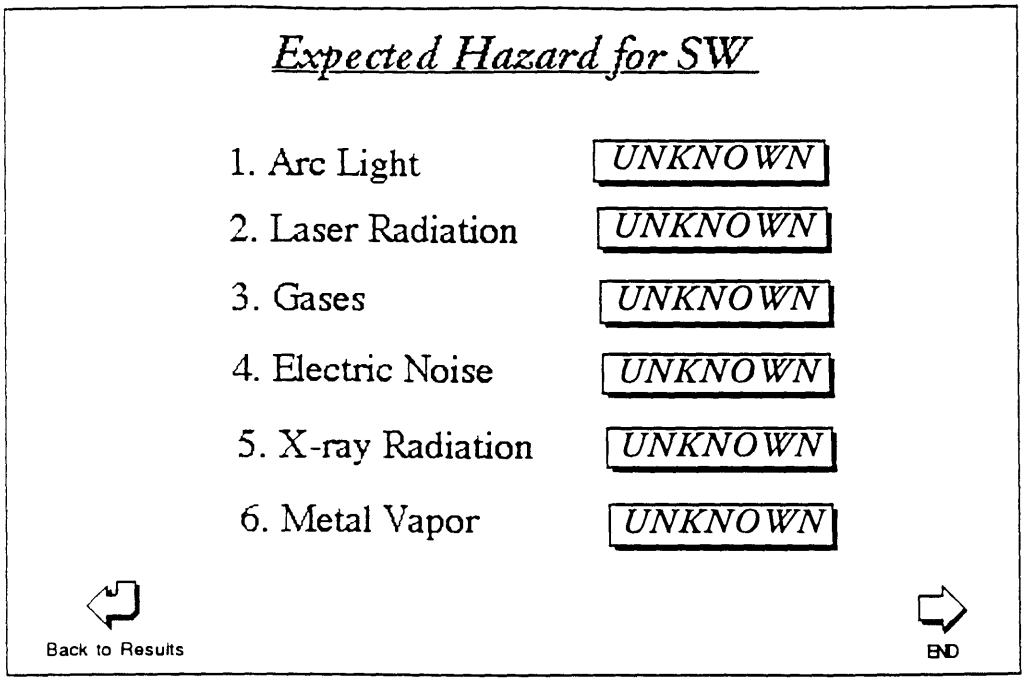

Expected Hazard for PAW
1. Arc Light
Yes
2. Laser Radiation
No
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

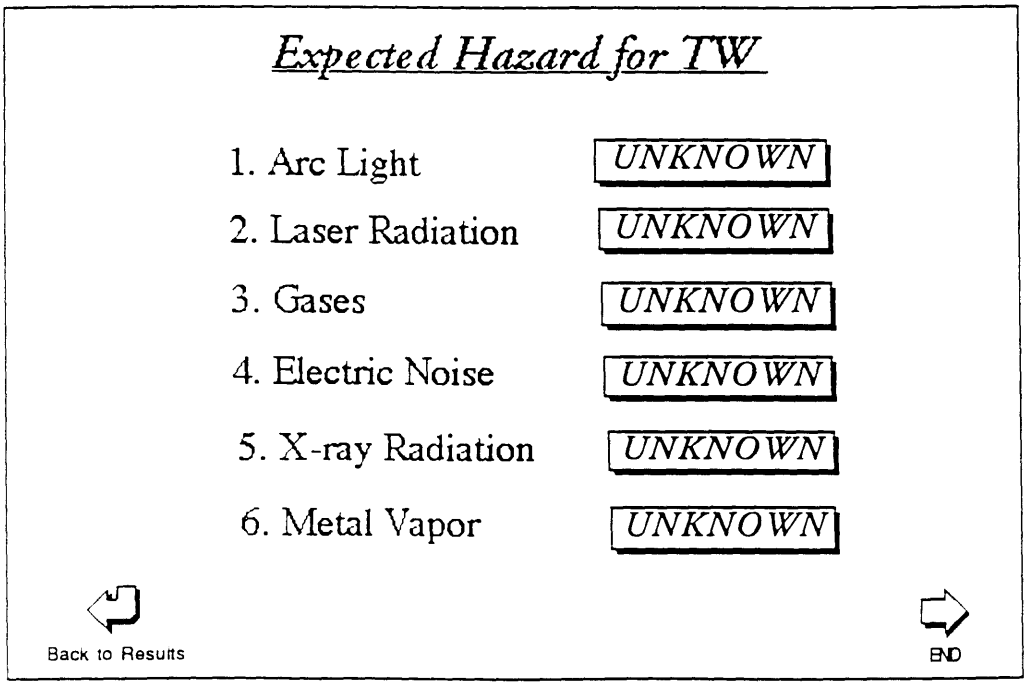

Expected Hazard for LBW
1. Arc Light
No
2. Laser Radiation
Yes
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

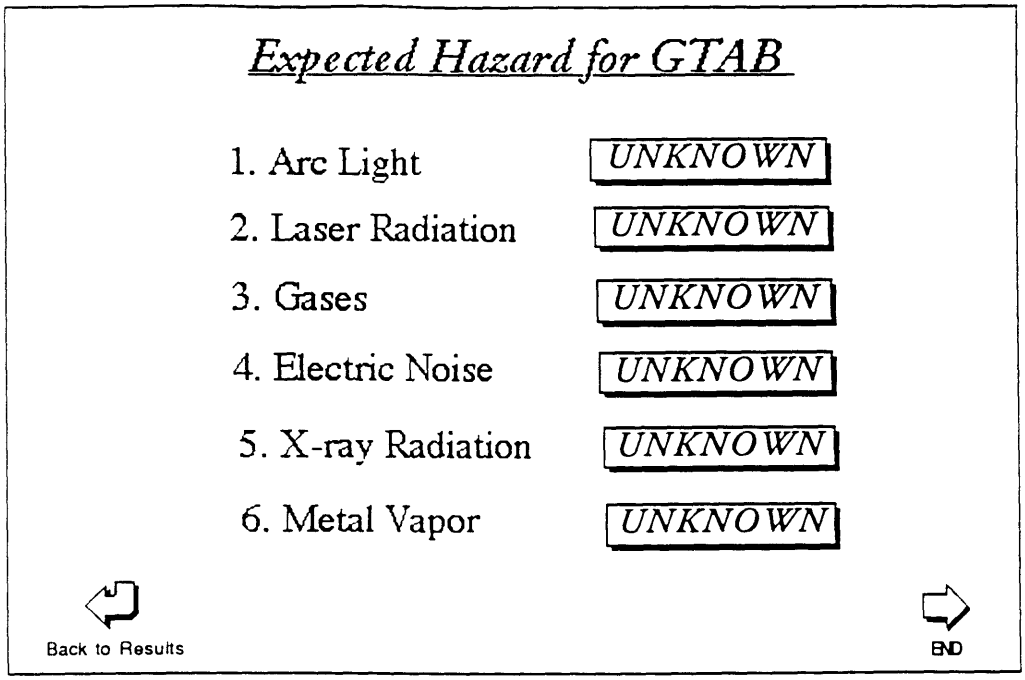

Expected Hazard for EBW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

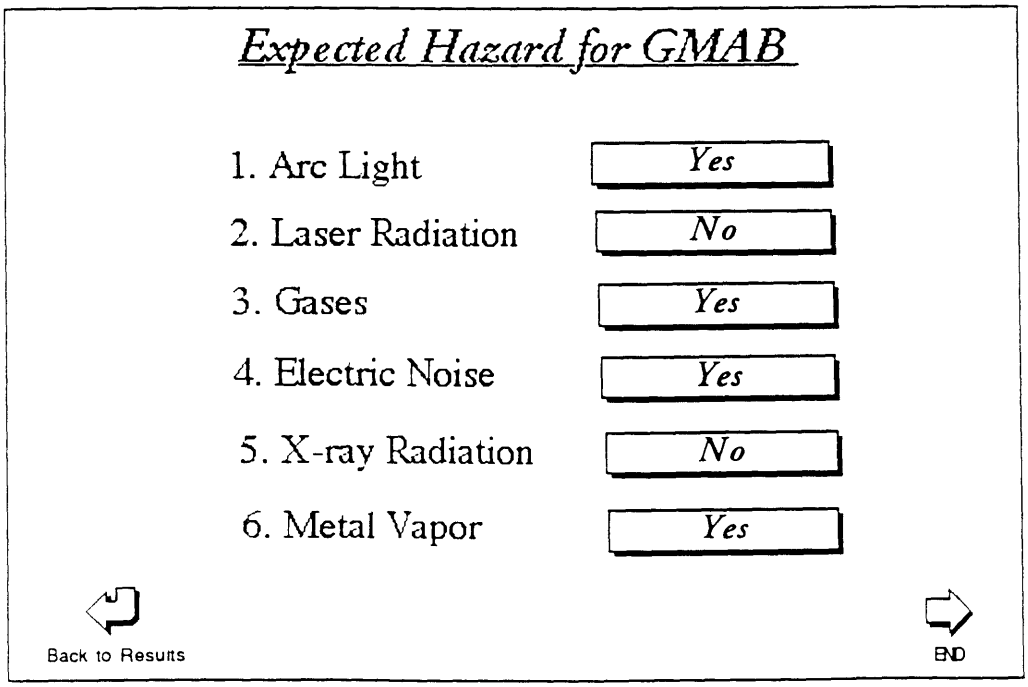

Expected Hazard for RW
1. Arc Light
No
2. Laser Radiation
No
3. Gases
No
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
No
Back to Results
END

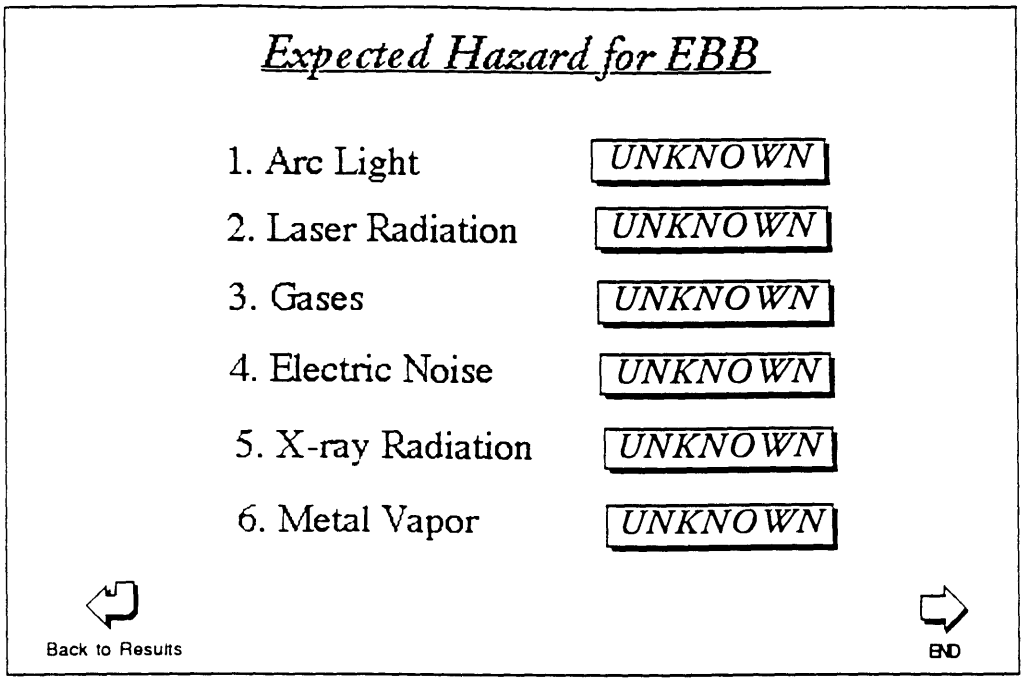

Expected Hazard for FW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END

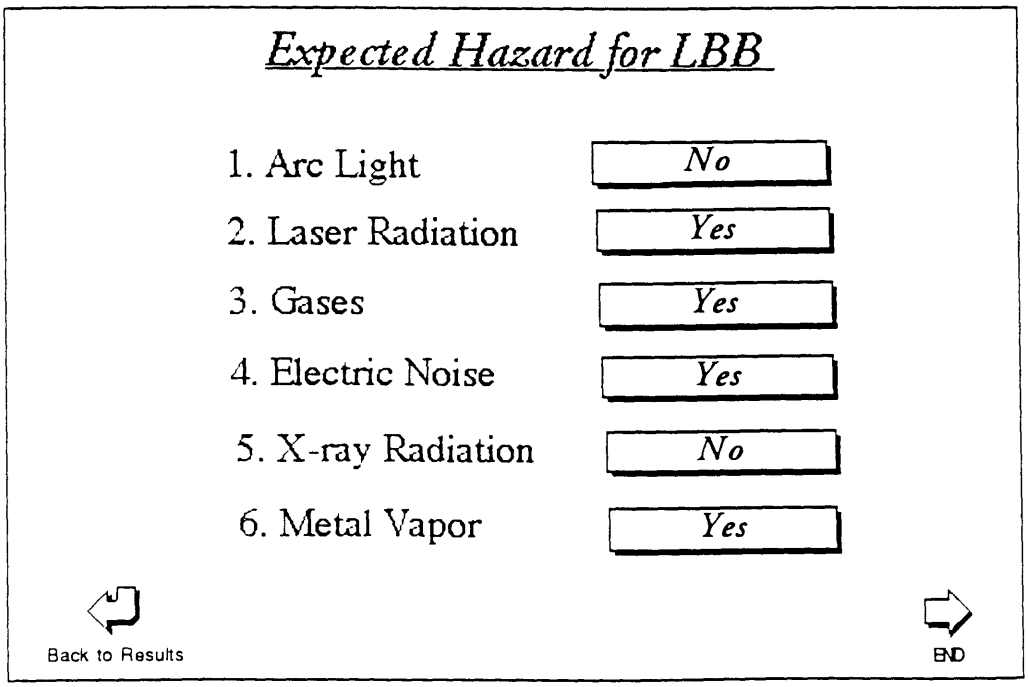

Expected Hazard for SW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for TW
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for GTAB
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for GMAB
1. Arc Light
Yes
2. Laser Radiation
No
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END


Expected Hazard for EBB
1. Arc Light
UNKNOWN
2. Laser Radiation
UNKNOWN
3. Gases
UNKNOWN
4. Electric Noise
UNKNOWN
5. X-ray Radiation
UNKNOWN
6. Metal Vapor
UNKNOWN
Back to Results
END


Expected Hazard for LBB
1. Arc Light
No
2. Laser Radiation
Yes
3. Gases
Yes
4. Electric Noise
Yes
5. X-ray Radiation
No
6. Metal Vapor
Yes
Back to Results
END

Chapter 9: Conclusion

A prototype of the computer-aided system has been developed in this research. It can be expanded further by integrating all the available information on welding in space. It is hoped that someday the improved version of this system may be used in constructions, maintenance, and repairs of real space structures.

This system is a part of the "Space Welding Guidebook" which is currently being developed by Professor Koichi Masubuchi and his staff at Massachusetts Institute of Technology. This system also can provide useful information to research groups interested in space welding work under possible areas for future research.

The system could satisfy the initial objectives which are as follows:

1. Ease of knowledge addition/deletion

2. Ability to make a selection using currently available data, even if we have only a limited amount of information

3. Ability to show the future research direction by a research indicator, which is attached to each knowledge

4. Its potential to become a real expert in metals joining processes as the knowledge database grows.

The author believes that the system will be the important step in the development of space fabrication technology in space, especially welding.

References

[1] Aaron, J., Gabris, A. E., Sulzman, M., F., Conners, M. M., and Pilcher C., "Making a home in space," *Aerospace America*, (Apr. 1989)

[2] Abe, Y., Fujiwara, M., Yasuda, C., Nayama, *R., and Okazaki, H., "Aircraft experiment to research on physical phenomena under micro-gravity," Mitsubishi Heavy Industry Technical News*, Vol. 27 No.6 (Nov. 1990)

[3] Agapagis, J. E., Masubuchi, K., and Alt, V. C., "Fundamentals and advances in the development of remote welding fabrication systems," *Welding Journal,* (Sep. 1986)

[4] Anderson, D. E., "EVA/Telerobotic space vehicle construction techniques-results of neutral buoyancy testing," Welding in Space and the Construction of Space Vehicles by Welding: Proceedings from the conference, (Sep. 24-26, 1991)

[5] Anderson, R. H., "EVA/Telerobotic fluid line repair tool development," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[6] Arata, Y., Abe, N., and Oda, T., "Fundamental phenomena in high power CO2 laser welding (Report I)," *Transactions of JWRI*: Atmospheric laser welding, (1985)

[7] Arata, Y., Abe, N., and Oda, T., "Fundamental phenomena in high power CO2 laser (Report II)," *Transactions of JWRI*: Vacuum laser welding, (1985)

[8] Arrowsmith, D. J., Clifford A.W., Moth, D.A. and Davies R. J., *Adhesive Bonding of Aluminum-Lithium Alloys*, (1986)

[9] Bakushin, S. V., Demidov, D. L., Morozov, Y. D., Nikitskii, V. P., and Churilo, I. V., "Prediction of structural materials performance at long-term service in space conditions," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[10] Bekey, I., "NASA's plans for manned missions to the Moon and Mars," *Spaceflight*, Vol. 31, (Sep. 1989)

[11] Bement, L. J., *Explosive Tube-to-Fitting Joining of Small-Diameter Tubes,* N86-11239 (1986)

[12] Bernold, L., "Common characteristics of terrestrial and space construction," *Journal of Aerospace Engineering*, Vol. 1, No. 4, (1988)

[13] Brahney, J. H., "Redesign of the challenger solid rocket motor joints," *Aerospace Engineering*, (Feb. 1988)

[14] Brahney, J. H., "Almost all composite helicopter," *Aerospace Engineering*, (May 1988)

[15] Brown, A. S., "Spreading spectrum of reinforcing fibers," *Aerospace America*, (Jan. 1989)

[16] Buckley, J. D. and Stein B. A., "Welding, bonding, and fastening 1984," *NASA Conference Publication 2387* (1985)

[17] Bulastev, A. R., Morejnis, M. M., Skorobogatov, S. A., Motry, V. I., Samilov, V. N., and Beleskii, D. V., "Erection and welding of large-sized structures in space," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[18] Cary, H. B., "Variable polarity plasma arc, keyhole welding of aluminum," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[19] Casey B., *Joining Processes in Space*

[20] Chandler, D. L., "NASA unveils 20-year plan for manned trips to Mars," *The Boston Globe*, (Dec. 20, 1988)

[21] Clark, P. S., "The Soviet space year of 1982"

[22] Clark, P. S., "Soviet space activity, 1985-1986"

[23] Davis, N. W., "Japan takes charge," *Aerospace America*, (Mar. 1988)

[24] Davis, N. W., "Japan broadens its aerospace interests," *Aerospace America*, (Mar. 1989)

[25] Davis, R., "Satellite repair program," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[26] DeMeis, R., "Deciphering clues to Soviet composites," *Aerospace America*, (Jan. 1988)

[27] DeMeis, R., "Shuttling to the space station," *Aerospace America*, (Mar. 1990)

[28] Dorward, R. C. and Pritchett, T. R., "Advanced aluminum alloys for aircraft and aerospace applications," *Materials & Design*, Vol. 9, No. 2, (1988)

[29] Dursch, H. W. and Spear, W. W., "Investigation into the existence of on-orbit coldwelding ," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26 1991)

[30] Dzhanibekov, V. A., Zagrebelny, A. A., Gavrish, S. S., Stesin, V. V., Shelyagin, V. D., Yurchenko, N. N., and Markov, A. V., "Welding equipment for space applications," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[31] Editor, "Space station program faces EVA, weight and power problems," *Spaceflight*, Vol.32, (Sep. 1990)

[32] Engquist, R. D. and Nord, D. B., *Study of Space Environment Fabrication and Repair Techniques:* Feasibility report: Contact NAS 9-4548 (1966)

[33] Engquist, R. D. and Nord, D. B., *Study of Space Environment Fabrication and Repair Techniques*: Final report: Contact NAS 9-4548, pp66-275 (1966)

[34] Froes, F. H., *Aerospace Materials for the Twenty First Century*

[35] Gutow, D. and Smith, M., "Sensors guide shuttle welding," *Welding Design & Fabrication*, (May 1990)

[36] Harf, F. H., Piccone, T. J., Wu, Y., Flemings, M. C., Shiohara, Y., Gardner, L. B., and Winsa, E. A., *The Alloy Undercooling Experiment on the Columbia STS*

61-C Space Shuttle Mission: NASA Technical Memorandum 88909, AIAA-87-0506 (1987)

[37] Hirzinger, G., "West Germany's first space robot," *Aerospace America*, (Aug. 1989)

[38] Johnson, S. W. and Leonard, R. S., "Engineering test support for construction in space," *Journal of Aerospace Engineering*, Vol. 1, No.4, (1988)

[39] Judd, M. D., *Materials for Space Applications*: Materials in Aerospace, Vol. II Proceedings

[40] Kaihara, S., Nakamura, T., Murayama, T., Irisama, T., and Kohno, T., "Cold solid-phase welding under ultra-high vacuum and pure argon gas atmospheres: Development of cold-solid phase welding (Report 1)," *Quarterly Journal of the Japan Welding Society*, Vol. 8, No. 4, (1990)

[41] Katsiya, K. V., Podyapolskii, G. V., and Yampolskii, V. M., "Welding thin metals in a vacuum with a magnetically controlled arc," *Welding Production*, (Dec. 1983)

[42] Kaukler, W. F. and Workman, G. L., "Laser welding in space," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[43] Kazakov, V. A. and Nazarenko, O. K., "State-ofart and prospects of development of electron beam welding of aerospace vehicles," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[44] Kidger, N., "Salyut mission report, part 12," *Spaceflight*, Vol. 25, 1, (Jan. 1983)

[45] Kidger, N., "Salyut mission report, part 13," *Spaceflight*, Vol. 25, 3, (Mar. 1983)

[46] Kidger, N., "Salyut mission report," *Journal of the British Interplanetary Society*, Vol. 36, (1983)

[47] Kidger, N. and Young, S., "Cosmonauts face difficult repair: Spacewalk will reveal extent of Soyuz damage," *Spaceflight*, Vol. 32, (July 1990)

[48] Kinard, W., Martin, G. L., and O'Neal, R. L., "Degradation of materials properties in space - Overview of LDEF (Lon duration exposure facility)," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[49] Knott, K., Feuerbacher, B., and Chappell C. R., "Spacelab-1: An early space station for science and technology," *Acia Astronautica*, Vol. 9, No. 6-7, (1982)

[50] Masubuchi, K., "Welding in space," *Journal of the Japan Welding Society*, Vol. 59 No. 6, (1990)

[51] Kuchuk-Yatsenko, S. I., Cherednichok, V. T., and Semenov, L. A., "The flash-butt welding of aluminum alloys," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[52] Kuvin, B. F., "Welding in space: Questions remain," *Welding Design & Fabrication*, (May 1990)

[53] Lalwaney, N. S. and Linse, V. D., *Explosive Welding in the 1990's*, N86-11237 (1986)

[54] Lane, J., Lambros, S., Neupert, W., and Barrowman, J., *HRSO as a Space Station Spartan*, (Nov. 13, 1986)

[55] Langenbeck, S. L., Ekvall, J. C., Sakata, I. F., and Rainen, R. A., *Design Considerations of New Materials for Aerospace Vehicles* (1987)

[56] Lawrence, G. S. and Schollhammer, F. R., *Final Report on Hand-Held Electron Beam Gun and External Power Supply*: NAS 9-4501

(Jun. 1965-Oct. 1966)

[57] Leary, W. E., "NASA studying ways to redesign space station to meet budget cut," *New York Times*, (Nov. 9, 1990)

[58] Lee, T. J., "Into space; Into the future," *Aerospace Engineering*, (Nov. 1988)

[59] Leger, L., Visentine, J., and Santos-Mason, B., *Selected Materials Issues Associated with Space Station*: 18th International SAMPE Technical Conference (1986)

[60] Leonald, J. W., "Testing the design and placement of ORUs for robotic/EVA maintenance with computer-aided simulation," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[61] Lerner, E. J., "Robots on the space station," *Aerospace America*, (Jun. 1987)

[62] Lienau, H., Lowry, J. F., and Hassan, C. B., "Adaptation of a battery-powered electron beam device to perform an in-orbit welding experiment," *9th IEEE Annual Symposium of Electron, Ion, and Laser Beam Technology*, (May 9-11, 1967)

[63] Lin, C. S., "Laser welding Al-Li sheet joints," *Aerospace Engineering*, (Dec. 1988)

[64] Lipsett, F. R., "New opportunities in space; Research in," *Canadian Aeronautics and Space Journal*, Vol. 29, No. 1, (1983)

[65] Lobanov, L. M. and Pivtorak, V. A., "Holographic NDT examination of welded structures," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[66] Lopez, R., "Weld repair keeps jet flying," *Welding Design & Fabrication*, (Apr. 1990)

[67] Lyman, P. and Carl, S., *Status of the Space Station Operations Task Force*: Briefing to the Space Station Users Working Group, (Nov. 12, 1986)

[68] Makhnenko, V. I., "CAD-systems for space welded structure design taking into account residual welding stresses and possible defects," *Welding in Space and Construction of Space Vehicles by Welding*: Proceedings from the conference, (Sep. 24-26, 1991)

[69] Masubuchi, K. and Nayama, M., "Fusion welding experiments under low-gravity conditions using aircraft," Welding in Space and Construction of

Space Vehicles by Welding: Proceedings from the conference, (Sep. 24-26, 1991)

[70] Masubuchi, K. and Nakamura, T. "Computer-aided guidebook for space welding fabrication," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceeding from the Conference, (Sep. 24-26, 1991)

[71] Madubuchi, K., *Proposal for a Brant-in-Aid on Feasibility of Remotely Manipulated Friction Welding in Space*: Submitted to Welding Research Council, (1987)

[72] Masubuchi, K., *Experiments on Space Stud and Friction Welding*: Report and Proposal, (1990)

[73] Masubuchi, K. and Imakita, A., *Joining Technologies for Maintenance and Construction of a Space Station*, (1986)

[74] Masubuchi, K. and Imakita, A., *Joining Technologies for Maintenance and Construction in Space*, (1987)

[75] McCarthy, R. W., *A Survey of: Position Sensing Devices in Automatic Control*: 13.17 Welding Engineering, (1984)

[76] McClure, S. and DiPirro, M., "Welding of the superfluid helium on-orbit transfer (Shoot) flight demonstration tanks and hardware," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceeding from the conference, (sep. 24-26, 1991)

[77] Meade, L. E., *Adhesives for Aerospace*, N86-11249, (1986)

[78] Mikulas, M. M. and Dorsey, J. T., *An Investigated In-Space Construction Facility for the 21st Century*: NASA Technical Memorandum 101515, (1988)

[79] Nagabushaman, R. R., "Management guidelines for the evaluation and selection of the welding technologies for use in outer space," (1991)

[80] National aeronautics and Space administration: On-orbit servicing Steering Committee, *On-Orbit Servicing Experience: A Compilation of Lessons Learned*, 408-M&R-0302-0009, (Jun. 1990)

[81] National Space Development Agency of Japan, *Space Station*: In SErcgh of New Activity Location for the Humans

[82] New Initiatives Office & Satellite Servicing Systems Project Office of Satellite Services System Working Group, *Interface Design Consideration for Serviceable Satellites*, JSC23925, (Nov. 1898)

[83] Newman, N. and Pinckert, R., "Materials for the NASP", *Aerospace America*, (May 1989)

[84] Newton-Montiel, B., "Workshop launches welding in space research," *Welding Journal*, (Mar. 1990)

[85] Nishiguchi. K., Matsunawa, A., and Kitada,T., "Arc phenomena at low pressure atmospheres (Report 1) Characteristics of carbon arc at low pressure hydrogen atmosphere, *Journal of the Japan Welding Society*, Vol. 38, No.9 (1969)

[86] Nishiguchi, K., Matsunawa, A., and Kitada, T., "Arc phenomena at low pressure atmospheres (Report 2) Consumption characteristics of a graphic cathode and the correlation to the cathode mode," *Journal of the Japan Welding Society*, Vol. 39, No.1, (1970)

[87] Nishiguchi, K., Matsunawa, A., and Katayama, T., "Arc phenomena at low pressure atmospheres (Report 4) Probe measurement in low pessure arcs and discharge mechanism of cathode plasma ball," Journal of the Japan Welding Society, Vol. 44, No. 12, (1975)

[88] Nishiguchi, K. and Matsunama, A., "Arc phenomena in low pressure atmospheres (Report 3) Cathode and anode models in low pressure arc with nonconsumable electrodes," *Journal of the Japan Welding Society*, Vol.39, No.5, (1970)

[89] Nishiguchi, K. and Matsunawa, A., "Arc phenomena at low pressure atmospheres (Report 5) Consumption characteristics and anode model of a graphite anode in helium atmosphere," *Journal of the Japan Welding Society*, Vol.45, No.2, (1976)

[90] Nishiguchi, K. and Matsunawa, A., "Arc phenomena at low pressure atmospheres (Report 6) Consumption characteristics and anode mode of a graphite anode in hydrogen atmosphere," *Journal of the Japan Welding Society*, Vol. 45, No.3, (1976)

[91] Nunes, A. C. Jr., Bayless, O. E. Jr., and Wilson, W. A., *The Variable polarity Plasma Arc Welding Process: Its Application to the Space Schuttle External Tank*: NASA Technical Memorandum, NASA TM-86482, (1984)

[92] Nunes, A. C. Jr., Bayless, O. E. Jr., and Jones, C. S. III, Munafo, P. M., Biddle, A. P., and Wilson, W. A., *The Variable Polarity Plasma Arc Welding Process: Its Application to the Space Shuttle External Tank*: NASA Technical Memorandum, NASA TM-82532, (1983)

[93] Ostrovskii, O. E., Tashchilov, V. S., and Ishchenko, A. Y., "Technology of arc welding of aluminum alloy shell Structures," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[94] Paine, T. O., "The next 40 years in space," *Spaceflight*, Vol. 32, (Jan.1990)

[95] Papazoglou, V. J. and Masubuchi, K., "Numerical analysis of thermal stresses during welding including phase transformation effects," *Journal of Pressure Vessel Technology*, Vol. 104, (Aug. 1982)

[96] Papazoglou, V. J., Masubuchi, K., Goncalves, E., and Imakita, A., *Residual Stresses Due to Welding: Computer-Aided Analysis of Their Formation and Consequences*: The Society of Naval Architects and Marine Engineers, No 12, (1982)

[97] Paton, B. E., "Welding in space," *Welding Engineering*, (Jan. 1972)

[98] Paton, B. E., "State-of-art and prospects of development of aerospace engineering in the USSR," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[99] Paton, B. E. and Lapchinskii, V. F., *Materials Science Study of Specimens of Permanent Joints and Coating Made in Space*

[100] Paton, B. E., Pokhodnya, I. K., Marchenko, V. G., Fartushnii, V. G., Dubenko, G. P., Morosov, Y. D., Ponomarev, V. I., Lapchinskii, V. F., and Masalov, Y. A., *A Study of Electrode Melting and Metal Transfer in Welding under Conditions of Variable Gravitational Forces*: Paper 37, A80-28960, (1980)

[101] Paton, B. E., Djanibekov, V. A., Savitskaya, S. E., Zagrebelny, A. A., Nikitskii, V. P., and Lapchinskii, V. F., *Testing The Versatile Hand Electron Beam Tool in Space,"*

[102] Paton, B. E., Lapchinskii, V. F., Bulatsev, A. R., Balitskii, V. M., and Samilov, V. N., *Peculiarities (of Using Welding Processes for Fabrication and Repair of Large-sized Structures in Space*

[103] Paton, B. E., "Technological aspects of welding in space," *Welding and cutting* , (Mar. 1990)

[104] Peel, C. J., McDarmaid, D., and Evans, B., *Considerations of Critical Factors for the Design of Aerospace Structures Using Current and Future Aluminum-Lithium*

[105] Pickns, J.R., Langan, T. J., and Barta, E. *Weldability of A1-5Mg-2Li-0.1Zr alloy 01420,* (1986)

[106] Poorman, R. M. *Skylab M551 Metals Melting Experiment*: NASA Technical Memorandum, NASA TM X-64960, (May 1975)

[107] Powell, J. W., "Nauka modules"

[108] Powell, J. W., "Soviet space science"

[109] Price, R. O., "Phase 1 space station power system Developments[120] Price, R. O., "Phase 1 space station power system development," *Aerospace Engineering*, (1988)

[110] Price, R. O., "Space station energy storage system development," *Aerospace Engineering*, (Oct.1988)

[111] Rainey, P. A., *Space Station Servicing Scenario Study*: Presented to the Space Station Science User's Group, (Nov. 13, 1986)

[112] Stofan, A. J., *Space Station: The Next Logical Step*

[113] Ronald, Terence, M. F., "Advanced materials to fly high in NASP," *Advanced Materials & Processes*, (May, 1989)

[114] Ruoff, C. F., "Space robotics in the '90s," *Aerospace America*, (Aug. 1989)

[115] Russell, C., Poorman, R., Jones, C., Nunes, A., and Hoffman, D., *Considerations of Metal Joining Processes for Space Fabrication, Construction and Repair*

[116] Schollhammer, F. R., *Hand-Held Electron Beam Gun for In-Space Welding*, (1967)

[117] Schwinghamer, R. J., "Better welds for launch vehicles," *Aerospace America*, (Sep. 1987)

[118] Serlemitsos, A. T., Sebastian, M. S., and Kunes, E. S., "A flightworthy adiabatic demagnetization refrigerator for use in the advanced x-ray astrophysical facility/x-ray spectrometer, *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[119] Shapland, D. J., "The first spacelab payload (FSLP)," *Aeronautical Journal*, (Feb. 1983)

[120] Shimada, W. and Machida, K., "Characteristics of low pressure TIG arc and fundamental melting phenomena of base metal," *Journal of the Japan Welding Society*, Vol. 48 No.10 (1979),

[121] Shimada, W. and Hoshinouchi, S., "A study on bead formation 32by low pressure TIG arc and prevention of under-cut bead," *Journal of the Japan Welding Society*, Vol. 51 No3, (1982)

[122] Shulym, V. F., Lapchinskii, V. F., Demidov, D. L., Nikitskii, V. P., and Neznamova, L. O., "Peculiarities and future development of space

welding," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[123] Smith, H. M., "The effects of aluminum oxide on internal welding of aluminum in space applications," *MIT Thesis*, (1992)

[124] Smith, M., *The Effect of Vacuum on the Friction of Aluminum,* (1990)

[125] Paton, B. E., Djanibekov, V. A., Savitskaya, S. E., Zagrebelny, A. A., Nikitskii, V. P., and Lapchinskii, V. F., "Testing the versatile hand electron beam tool in space"

[126] Stein, B. A., *Rapid Adhesive bonding B and Field Repair of Aerospace Materials*, N86-11253, (1986)

[127] Stephens, J. R., "Composites boost 21st-century aircraft engines," *Advanced Materials & Processes,* (Apr. 1990)

[128] Reynerson, M. C., "Design considerations for remotely operated welding in space," *MIT Thesis*: Task Definition and Visual Weld Monitoring Experiment, (1993)

[129] Sykes, G. F., Joan, G. F., and Wane, S. S., *Assessment of Space Environment Induced Microdamage in Toughened Composite Materials*: 18th International SAMPE Technical Conference, (1986)

[130] Tarasenko, E. N., Kirsanov, Y. K., and Gorskii, V. I., "Electrostatic phase control of the arc discharge current with a hollow cathode in welding and surfacing in vacuum," *Welding Production,* (June 1984)

[131] Tashchilov, V. S., Shiganov, N. V., and Ishchenko, A. Y., "Materials for aerospace welded structures Part I: High-strength light alloys and structural Materials ," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[132] Tashchilov, V. S., Shiganov, N. V., and Yushchenko, K. A., "Materials for aerospace welded structures Part II: Steels and heat-resistant alloys,"

Welding in Space and the Construction of Space Vehicles by Welding: Proceedings from the Conference, (Sep. 24-26, 1991)

[133] Taylor, R. A., *A Space Debris Simulations Facility for Spacecraft Materials Evaluation*: 18th International SAMPE Technical Conference, (1986)

[134] Teren, F., *Space Station Electric Power System Requirements and Design*: NASA Technical Memorandum 89889, AIAA-87-9003, (1987)

[135] U.S. Office of Technology Assessment, *SALYUT: Soviet Steps Toward Permanent Human Presence in Space*, PB84-181437, (Dec. 1983)

[136] Volgin, L. A., Koroteev, A. Y., Malakovich, A. P., Petushkov, V. G., Sitalo, V. G., and Novikov, V. K., "Explosion welding and cutting in aerospace engineering ," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[137] Washburn, R. M., "Materials," *Aerospace America*, (Dec. 1988)

[138] Watson, J. K., "Engineering considerations for on-orbit welding Operations," *The Journal of the Astronautical Sciences*, Vol.34, No. 2, (1986)

[139] Willenberg, H. J., "Material processing: The sky is not the Limit," *Aerospace Engineering*, (May, 1988)

[140] Wolf, D. B. and Nicolay, R. C. "Welding nozzle extension for ARIANE launch vehicles," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[141] Workman, G. L., *Welding in Space Workshop*: Final Report, NAS 8-36955 D. O. 56, (1990)

[142] Workman, G. L., *Final Report on Contract Number NAS 8-36955 D. O. 56 Entitled Welding in Space Workshop*: Submitted to NASA, (1990)

[143] Yamamoto T. and Shimada, W. "A study of the arc welding phenomena at reduced gas pressures (report 1): Electric Characteristics of the tungsten arc

in argon atmosphere," *Journal of Japan Welding Society,* Vol. 38 No. 1, (1969)

[144] Yamamoto T. and Shimada, W. "A study of the arc welding phenomena at reduced gas pressures (report 2): Thermal characteristics of the tungsten arc in argon atmosphere," *Journal of Japan Welding Society,* Vol. 38 No. 7, (1969)

[145] Yamamoto T. and Shimada, W. "A study of the arc welding phenomena at reduced gas pressures (report 3): Penetration Formed by the Fixed TIG arc in the metal specimen," *Journal of the Japan Welding Society,* Vol. 39 No. 11, (1970)

[146] Yamamoto T. and Shimada, W. "A study of the arc welding phenomena at reduced gas pressures (report 4): Characteristics of arc and penetrations under axial gas flow," *Journal of the Japan Welding Society,* Vol. 40 No. 3, (1971)

[147] Zolotovsky, S. and Miguet, B., "Successful technology transfer from a research and development laboratory to an aerospace production unit," *Welding in Space and the Construction of Space Vehicles by Welding*: Proceedings from the Conference, (Sep. 24-26, 1991)

[148] Henon, B. K., "Automatic orbital GTA welding: Highest quality welds for tomorrows's high-performance systems"

[149] Hardwick, R., "Explosive welding of tubular configured joints for critical applications

[150] Bosworth, T. J., Miller, C. M., and Griffee, "Welding the space station common module prototype"

[151] Ando and Hasegawa, "The characteristics of TIG welding under low pressure," Welding Arc Phenomena

[152] NASA Marshall Space Flight Center: Its Place in NASA

[153] The Space Station Power System

[154] USSR Report: Space, JPRS-USP-84-006, (Nov. 14, 1984)

[155] Information Summarises: Space Station, PMS-008A(Hqs), (1988)

[156] "New radiator system designed for large spacecraft," Aerospace Engineering, (Jan. 1988)

[157] Station Break: A Monthly Newsletter on the Space Station Freedom Program, Vol. 2, No. 7, (Jul. 1990)

[158] Station Break: A Monthly Newsletter on the Space Station Freedom Program, Vol. 2, No. 4, (Apr. 1990)

[159] Station Break: A Monthly Newsletter on the Space Station Freedom Program, Vol. 2, (Feb. 1990)

[160] Overview - Soviet On-Orbit Welding System (URI), (1991)

Appendices

Appendix A
User Interface

Welcome to the Computer-Aided System
for
Space Welding

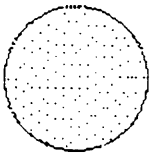
Start

Welding Location --*Click a location.*

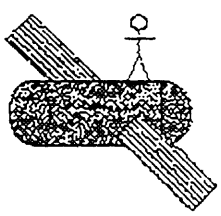

Earth Orbit


Moon

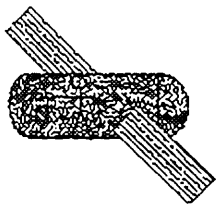

Mars


Other Location

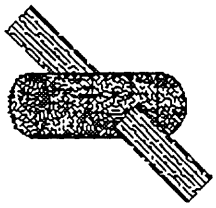
Extra- or Intra-vehicular Activity --*Click one.*



Extravehicular Activity



Intravehicular Activity
with
Gravity Control System



Intravehicular Activity
without
Gravity Control System

Environmental Conditions --*Put values.*

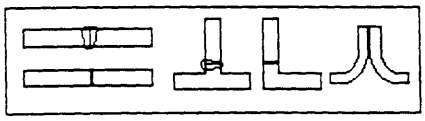
Pressure: OK atm

Gravity: OK G

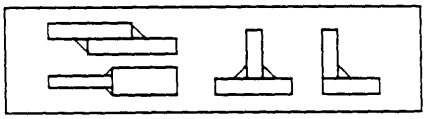
Temperature: OK K

OK

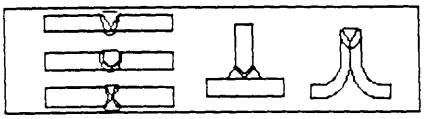
Weld Type --*Click one.*



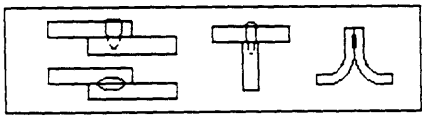
Square (I)



Fillet (F)



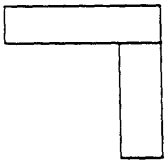
Groove (G)



Seam (S)

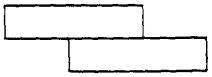
Joint Type --*Click one.*

Butt Joint

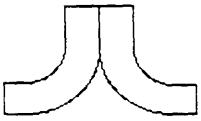


Corner Joint

T Joint



Lap Joint



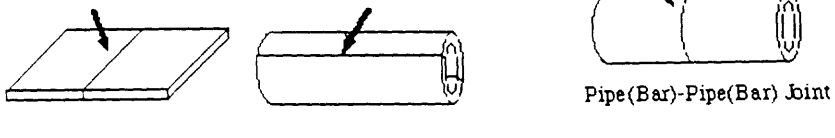
Edge Joint

Material --*Click one.*

Steels Aluminum Titanium

F.R.M. C-C Composite

Shape --*Click one.*



Pipe(Bar)-Pipe(Bar) Joint

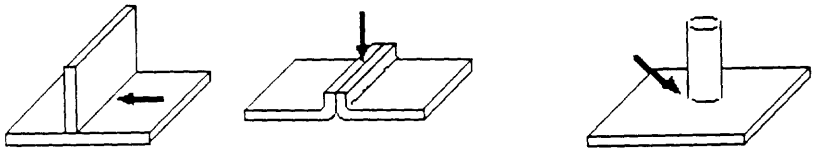
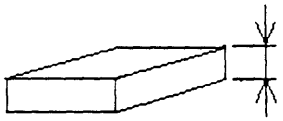


Plate-Plate Joint Pipe(Bar)-Plate Joint

Thickness, Power Capacity, Equipment Weight

--Put values.

1. Thickness



mm

2. Power Capacity

How much capacity is allowed to be used?

kw

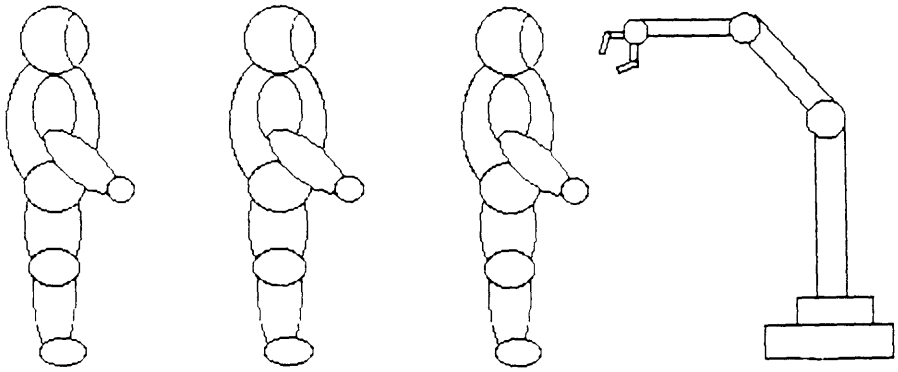
3. Equipment Weight

How much is the available weight of the welding equipment to be taken to the location of welding?

kg

OK

Operator *--Click one.*

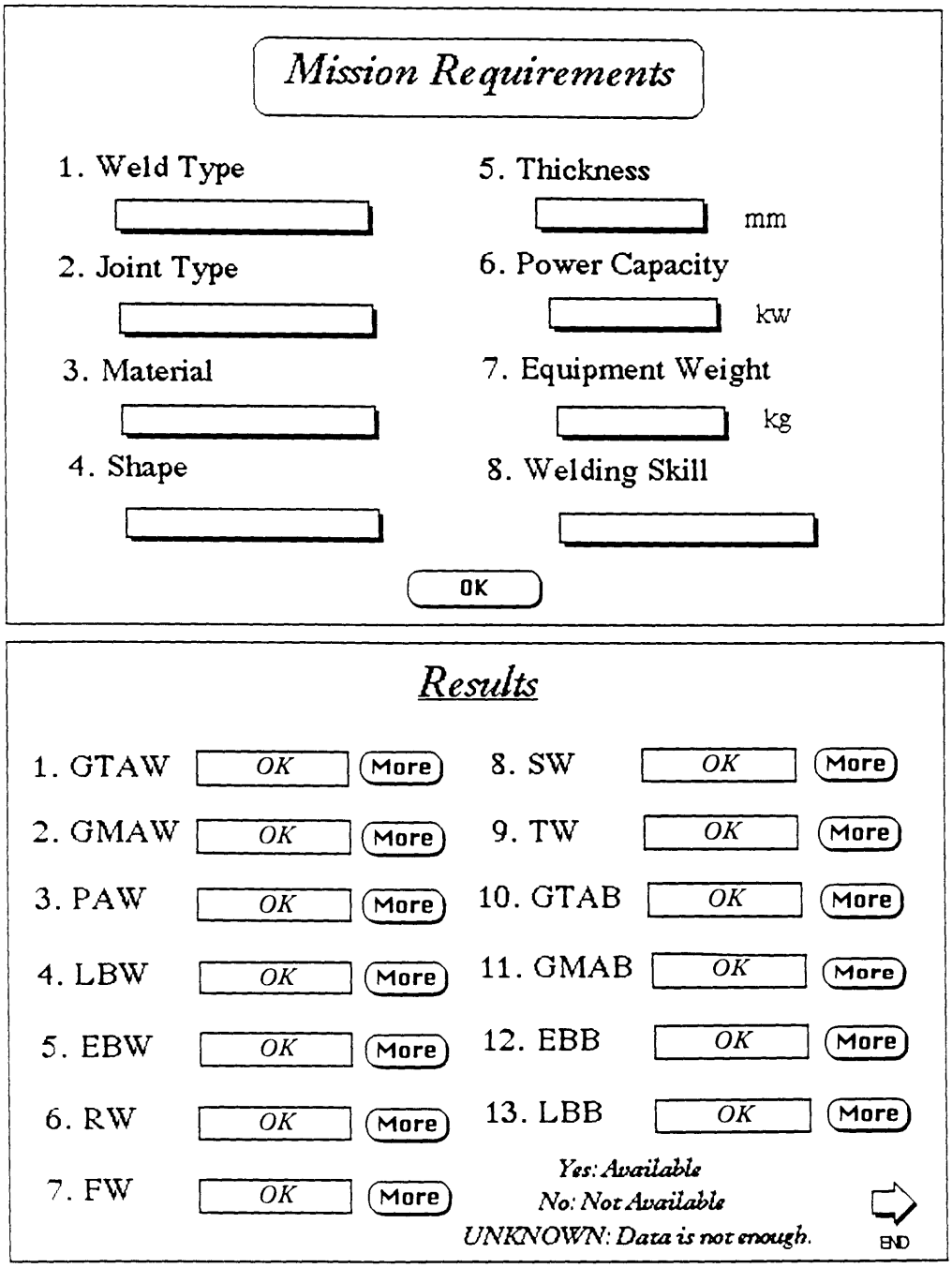


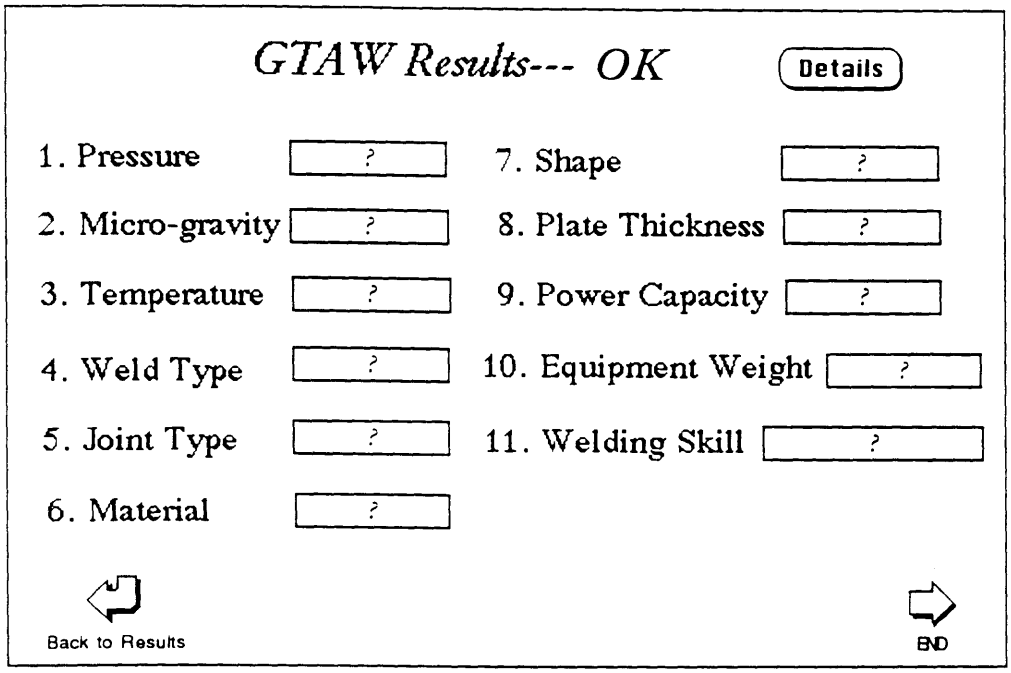
Astronaut (Expert in Welding) (With Assistant of Expert)

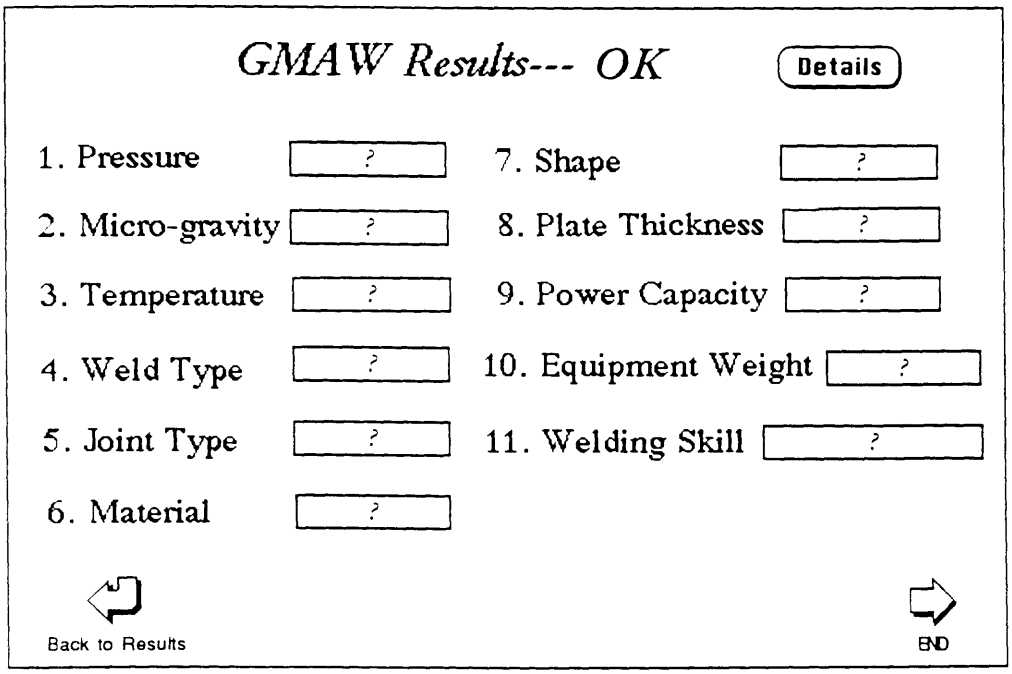
Astronaut (Intermediate in Welding)

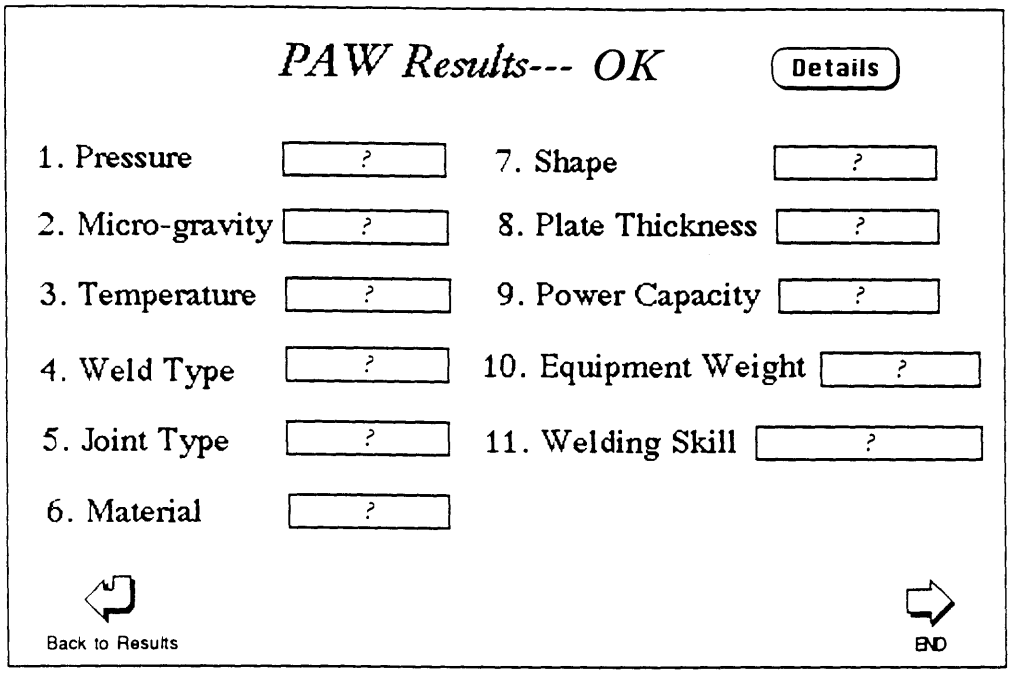
Astronaut (Novice in Welding)

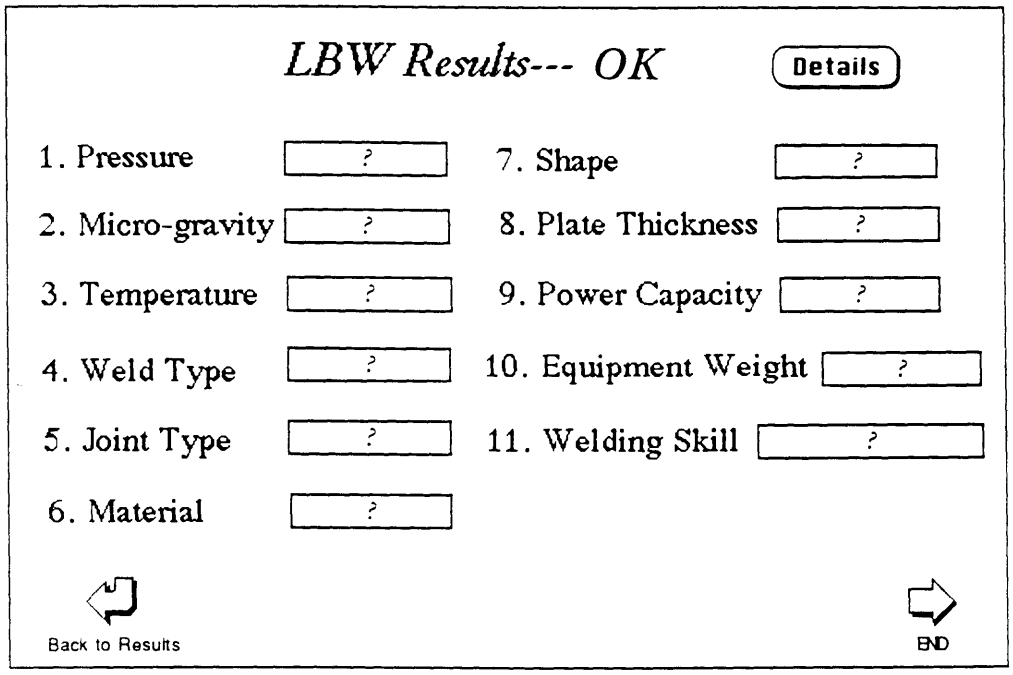
Robot

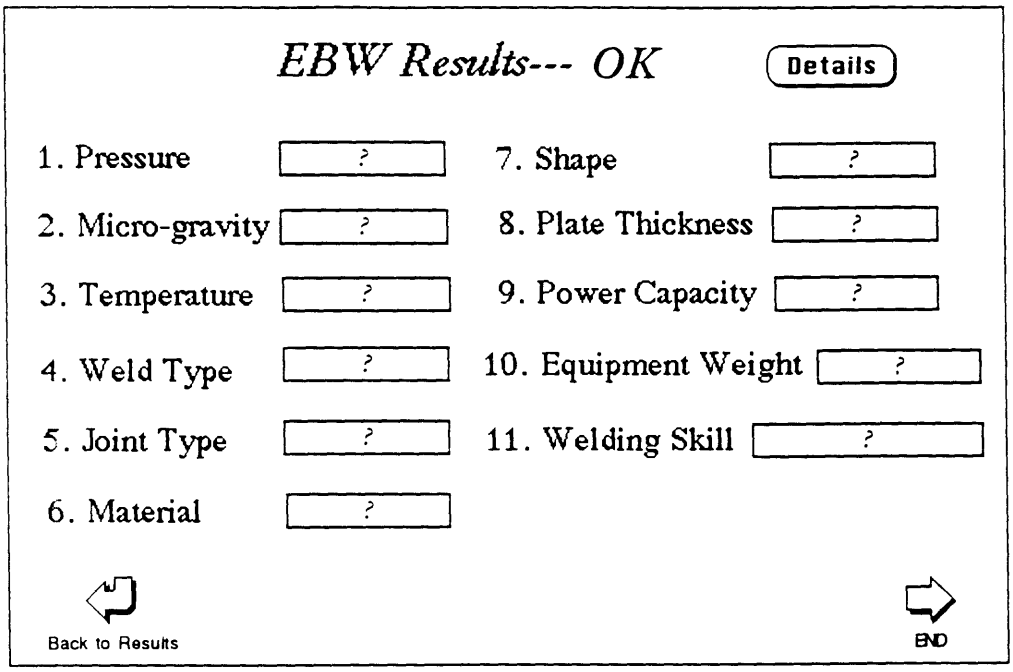

Mission Requirements
1. Weld Type
2. Joint Type
3. Material
4. Shape
5. Thickness
mm
6. Power Capacity
kw
7. Equipment Weight
kg
8. Welding Skill
OK
Results
1. GTAW OK More
2. GMAW OK More
3. PAW OK More
4. LBW OK More
5. EBW OK More
6. RW OK More
7. FW OK More
8. SW OK More
9. TW OK More
10. GTAB OK More
11. GMAB OK More
12. EBB OK More
13. LBB OK More
Yes: Available
No: Not Available
UNKNOWN: Data is not enough.
END

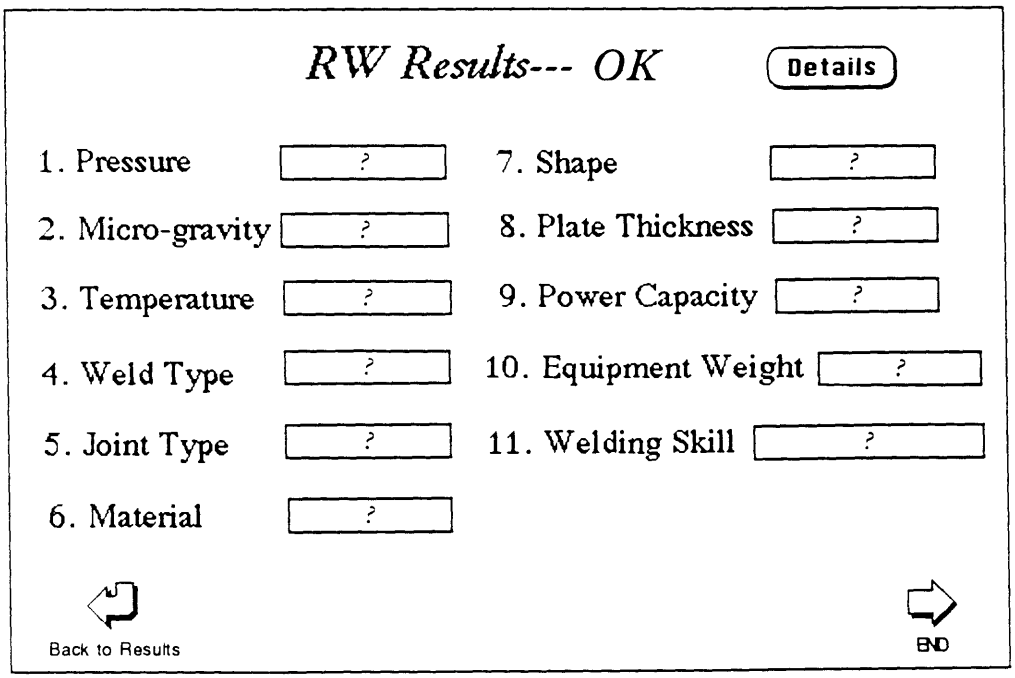

GTAW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

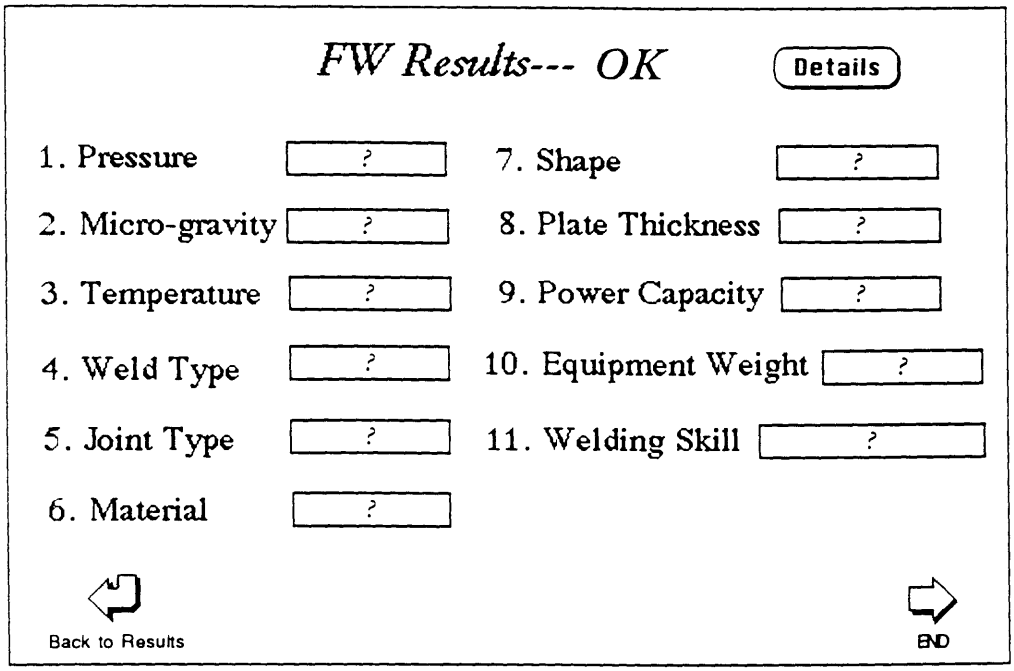

GMAW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

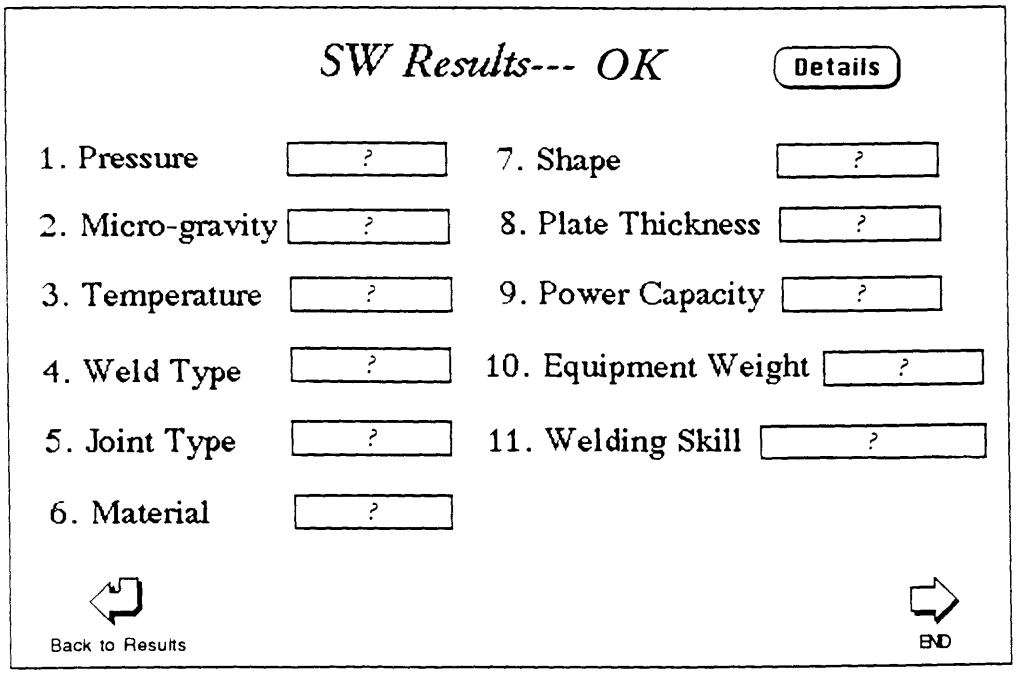

PAW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

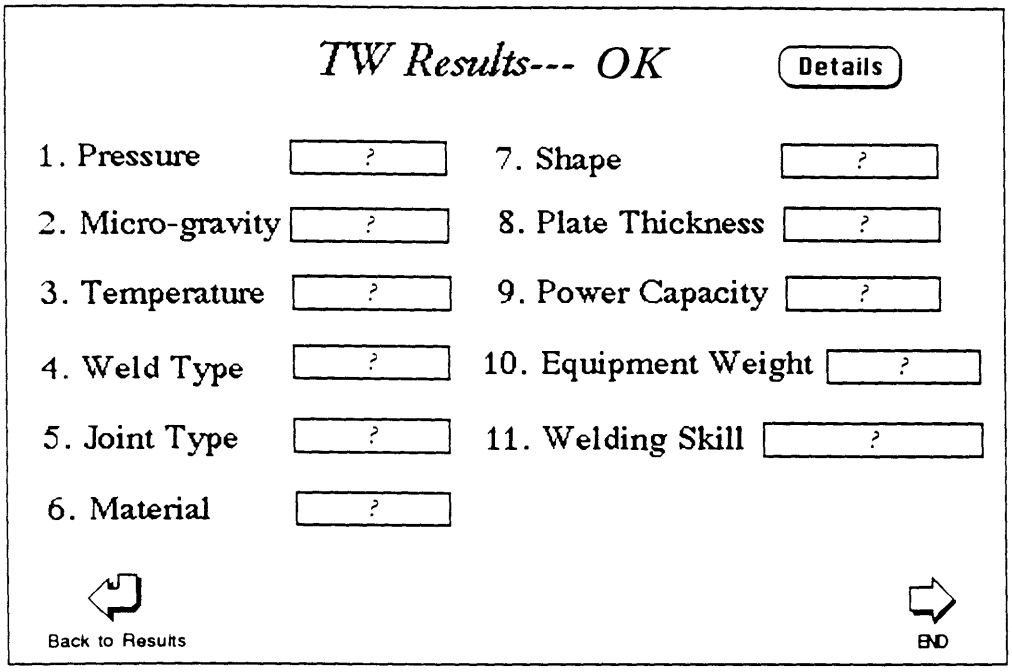

LBW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

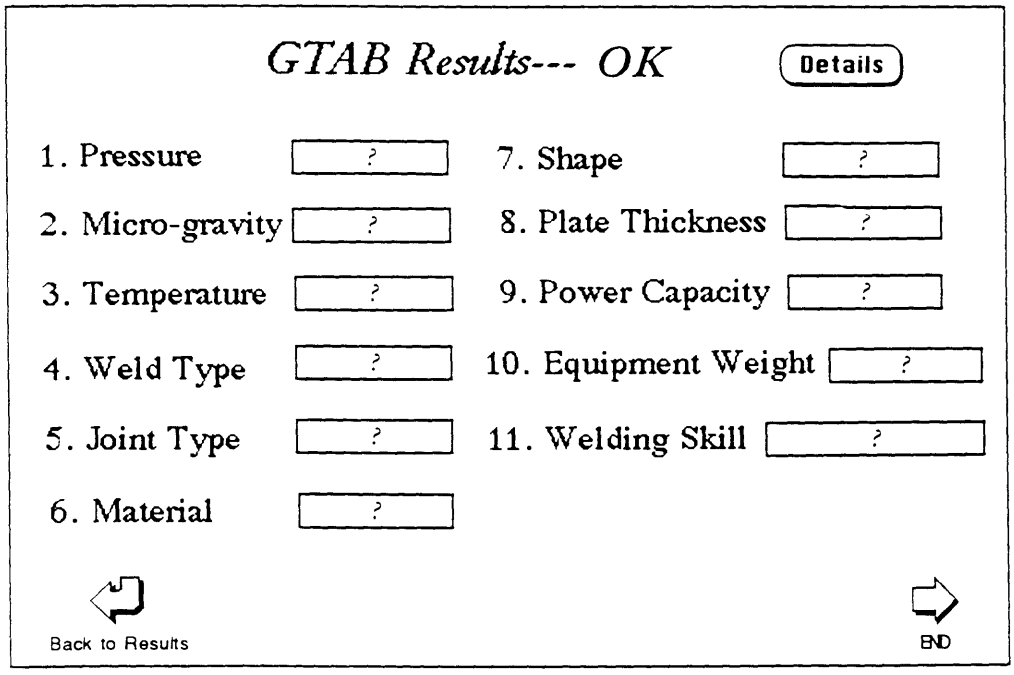

EBW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

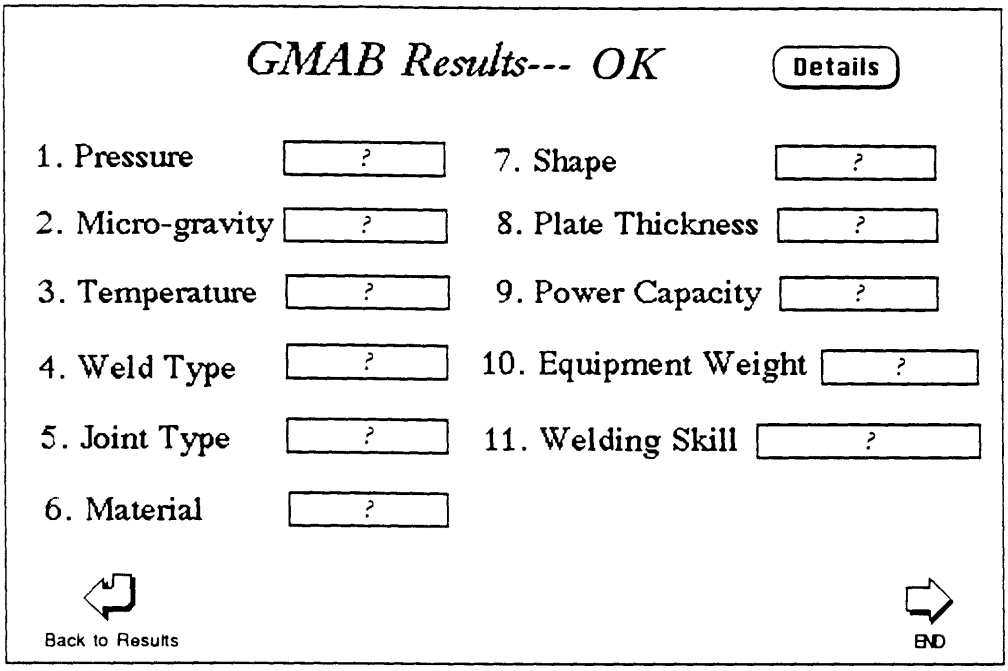

RW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

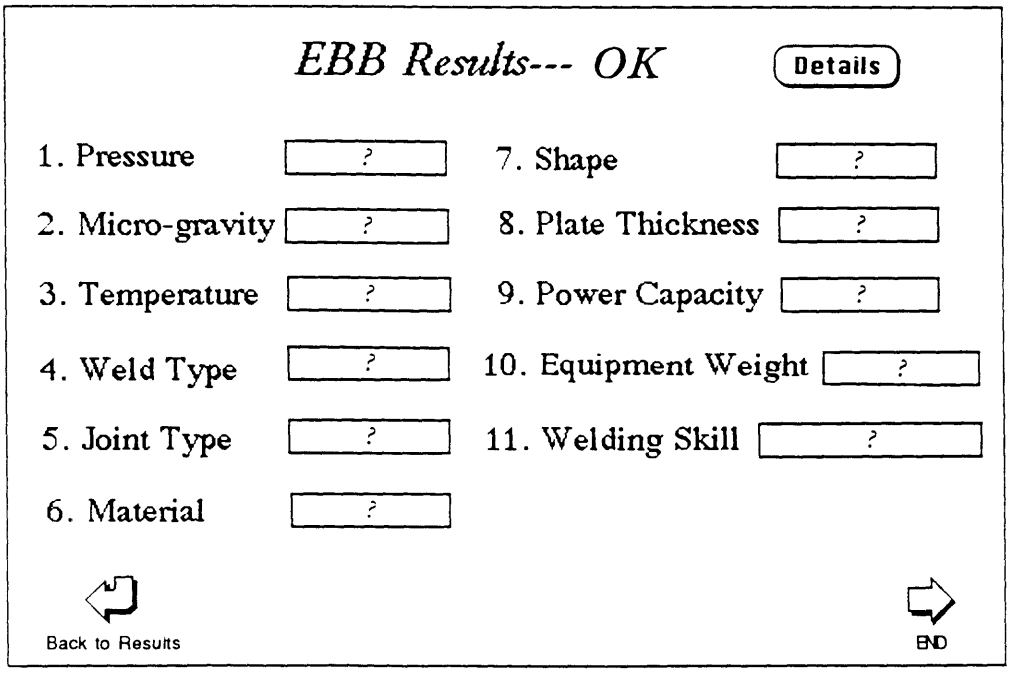

FW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

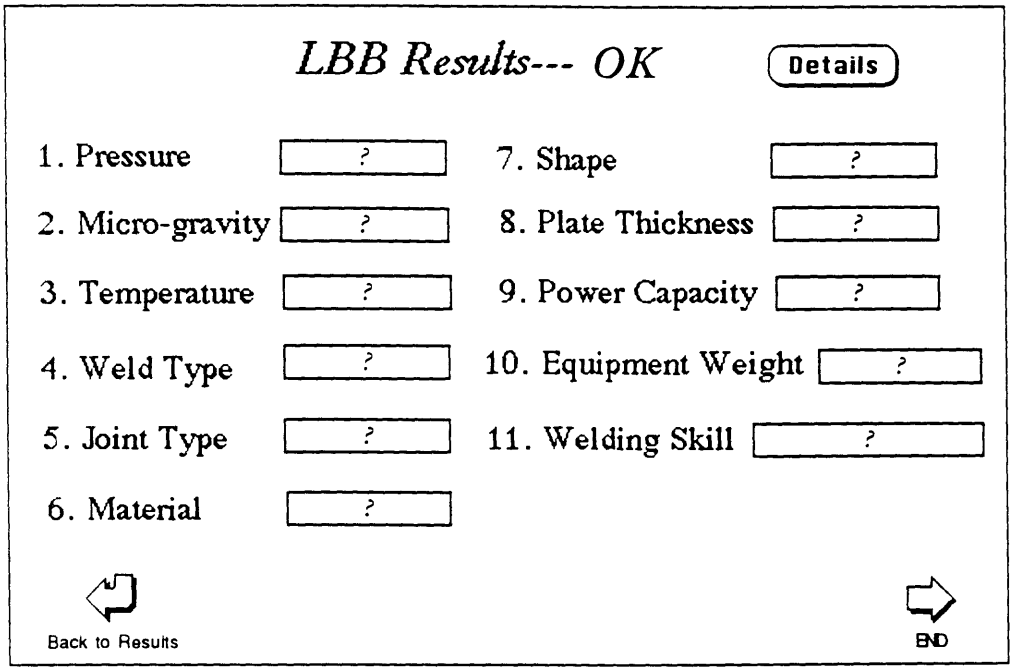

SW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

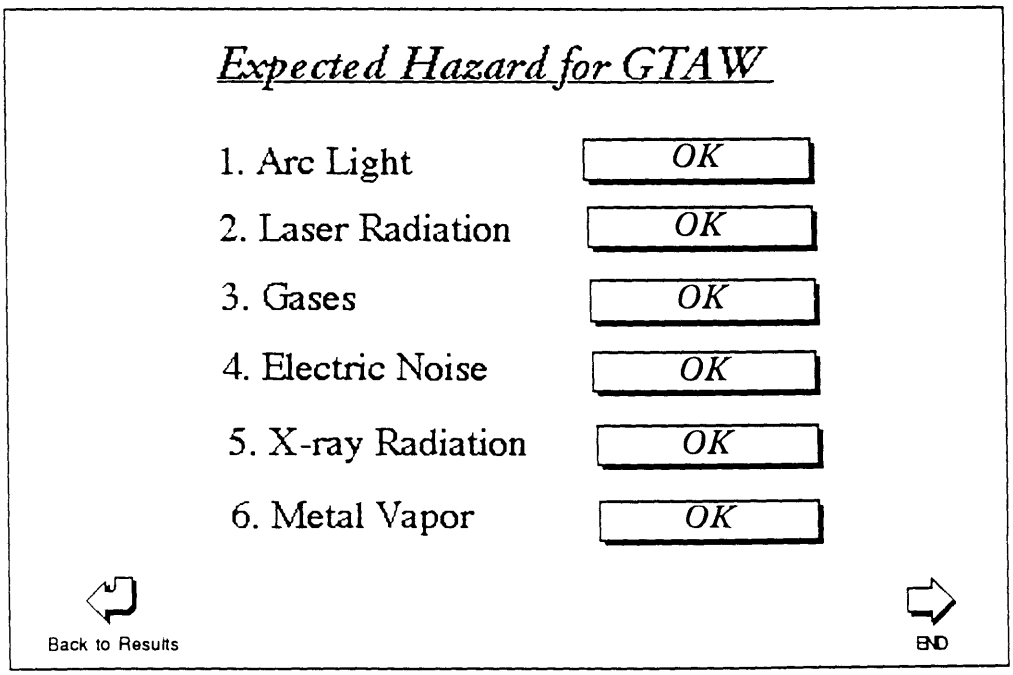

TW Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

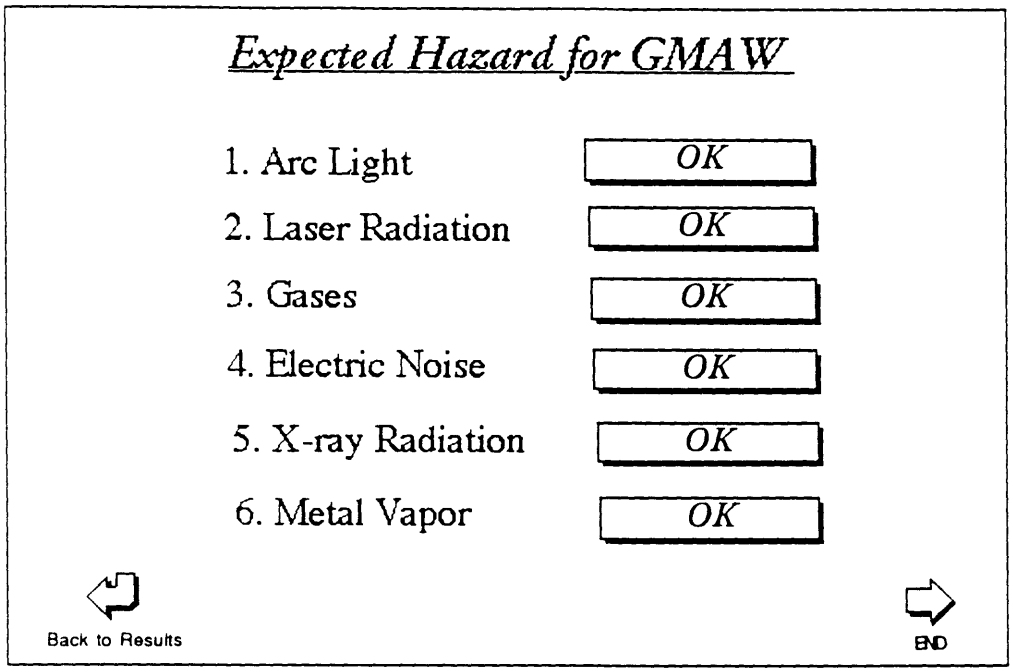

GTAB Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

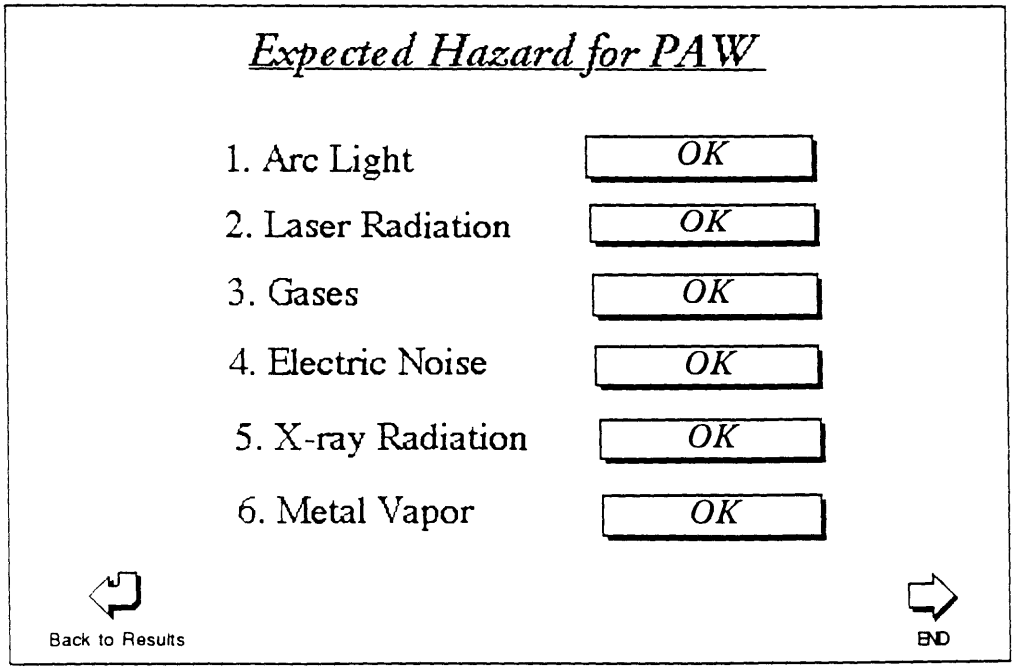

GMAB Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

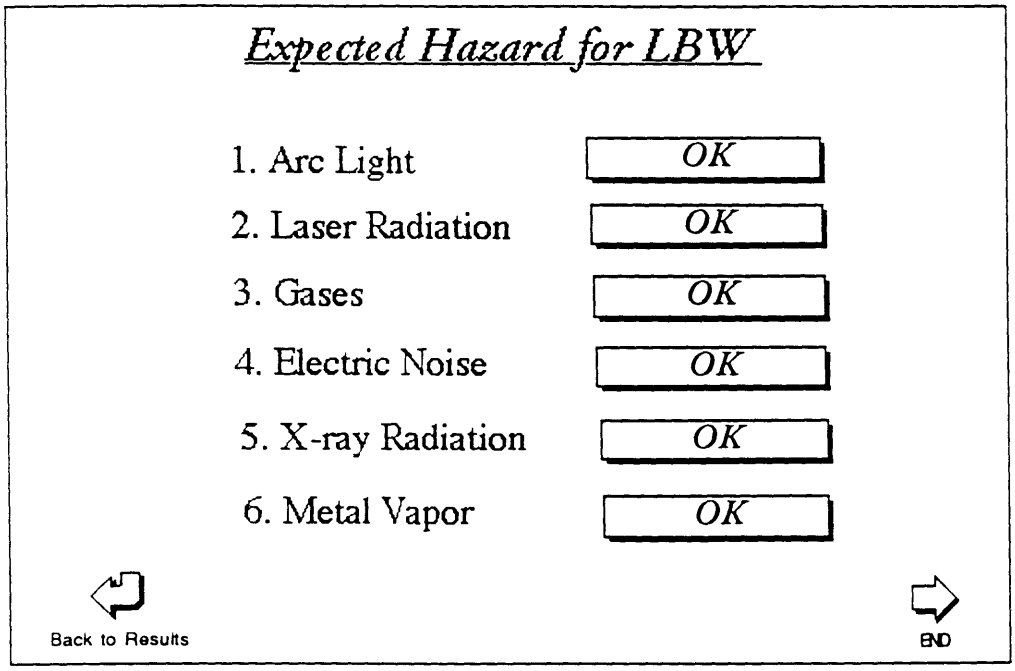

EBB Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

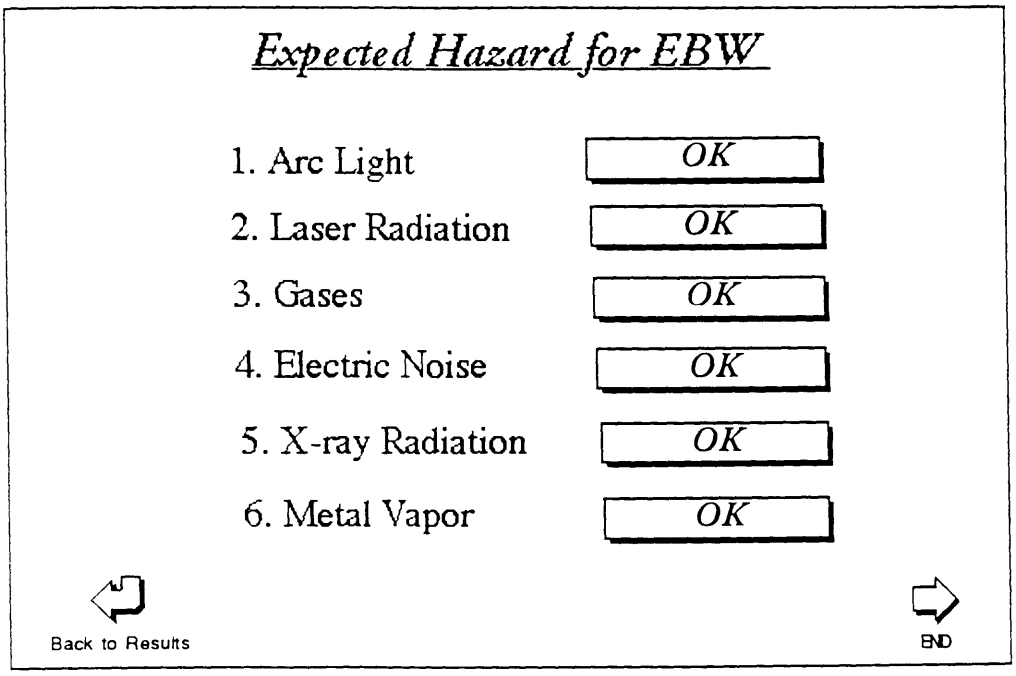

LBB Results--- OK
Details
1. Pressure
?
2. Micro-gravity
?
3. Temperature
?
4. Weld Type
?
5. Joint Type
?
6. Material
?
7. Shape
?
8. Plate Thickness
?
9. Power Capacity
?
10. Equipment Weight
?
11. Welding Skill
?
Back to Results
END

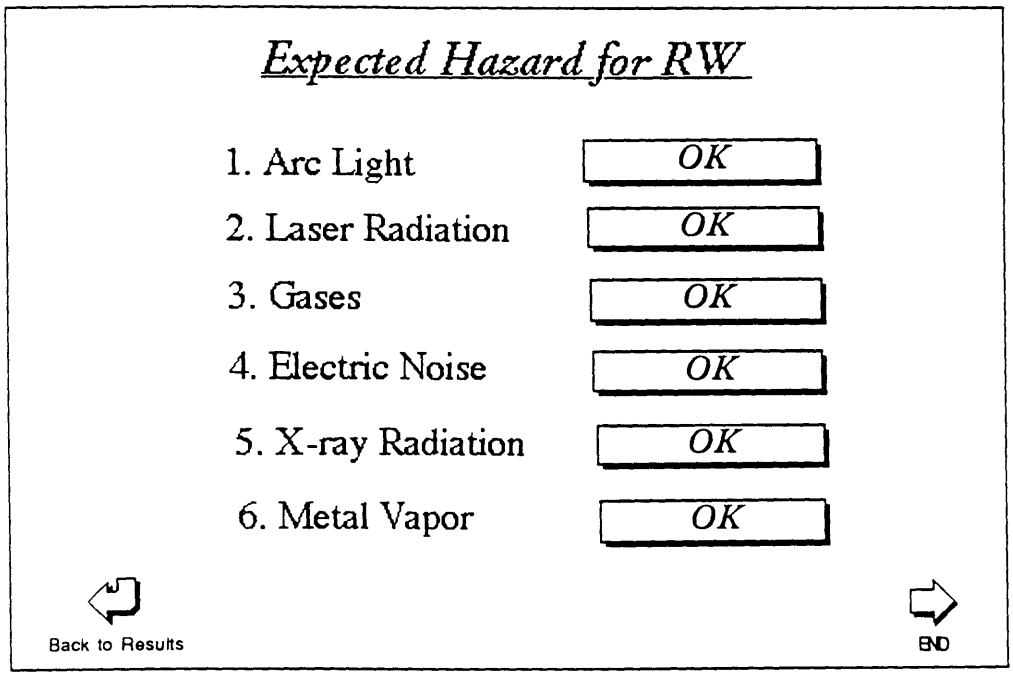

Expected Hazard for GTAW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

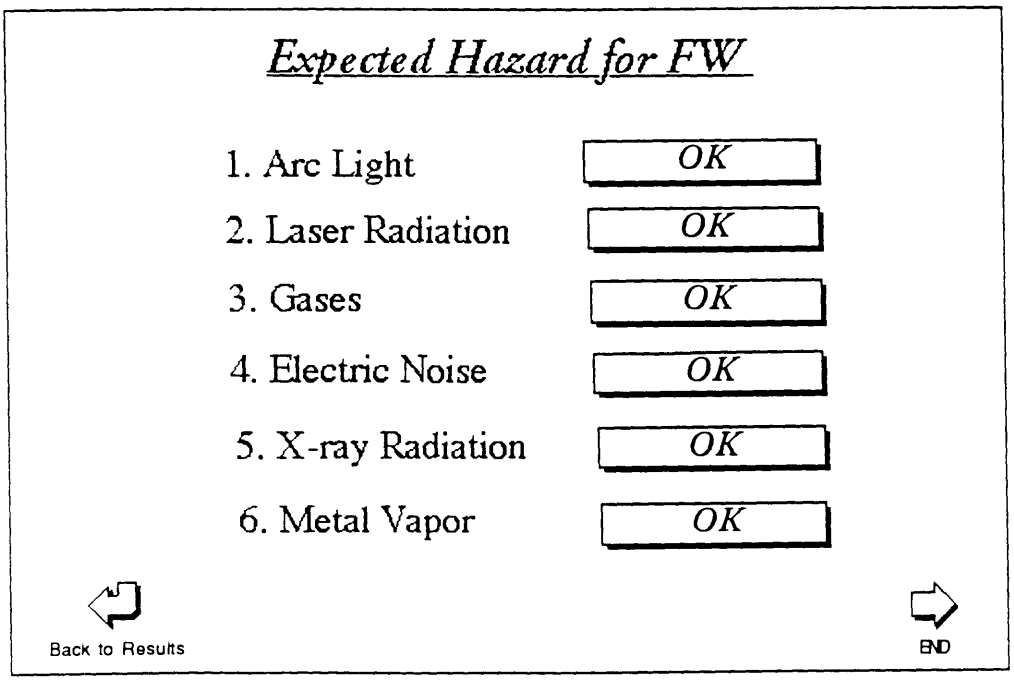

Expected Hazard for GMAW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

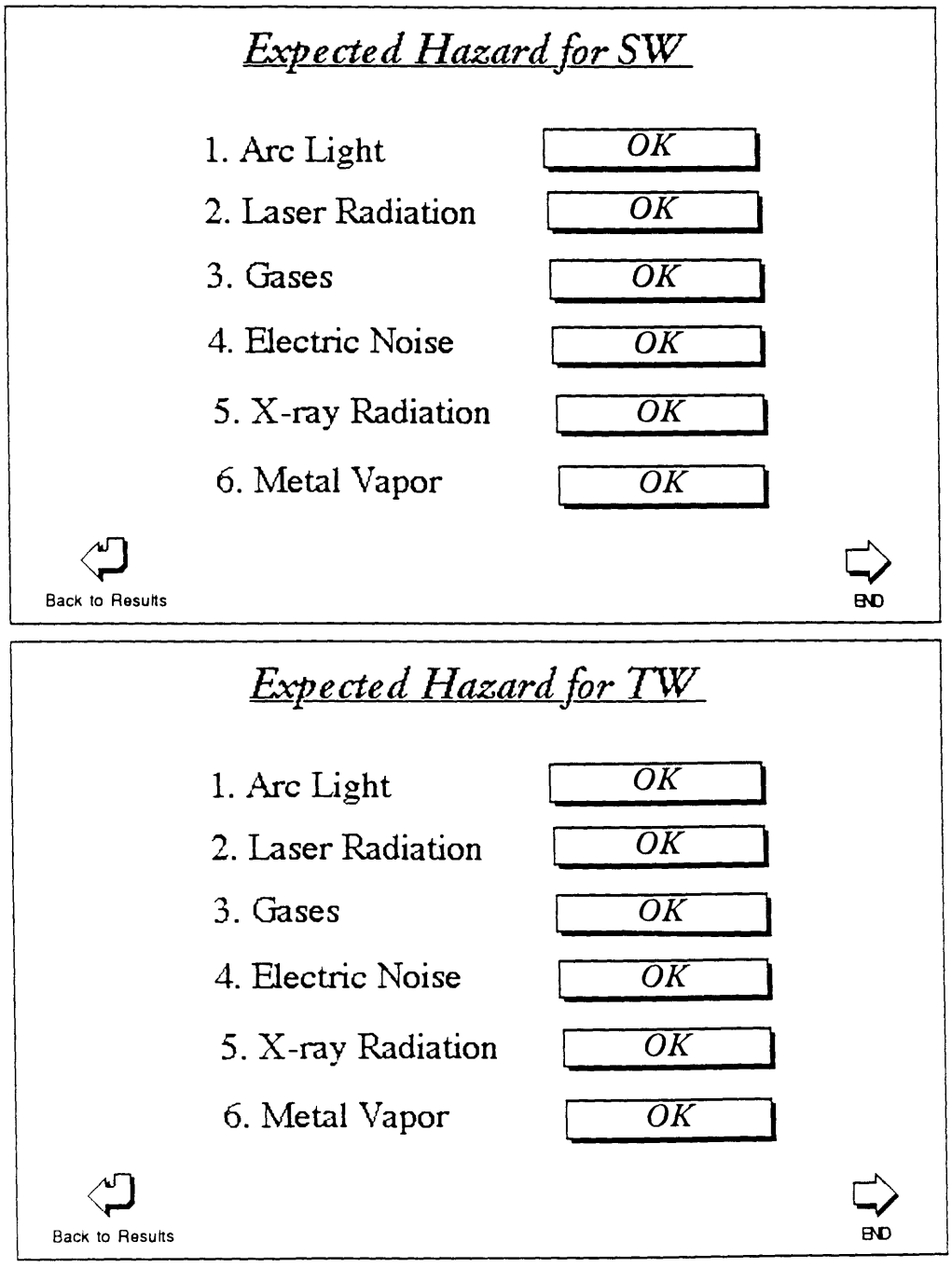

Expected Hazard for PAW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

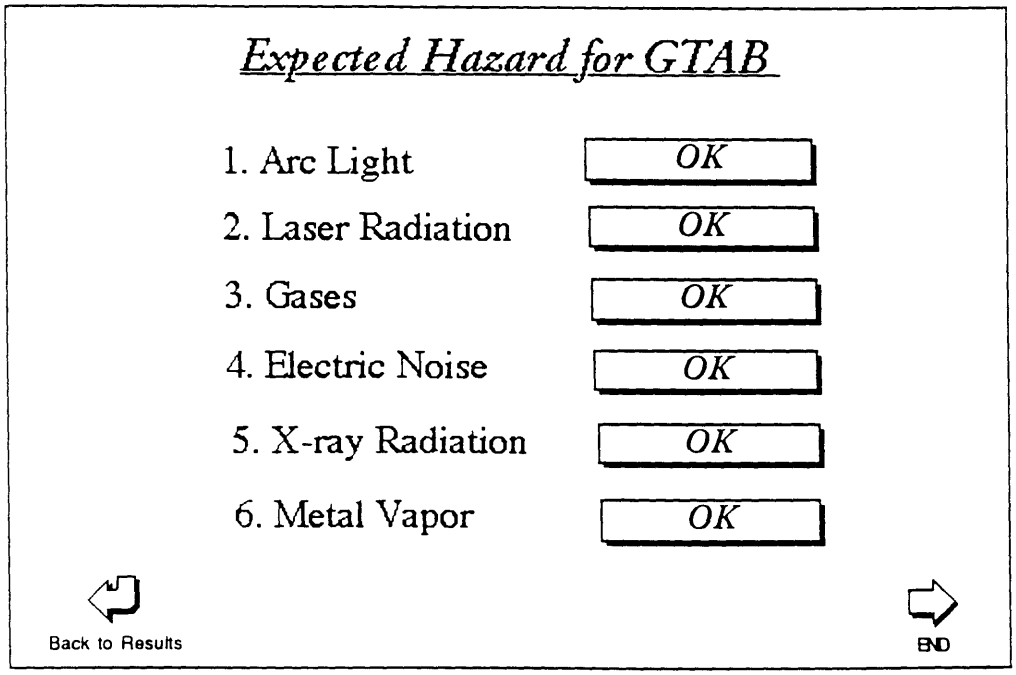

Expected Hazard for LBW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

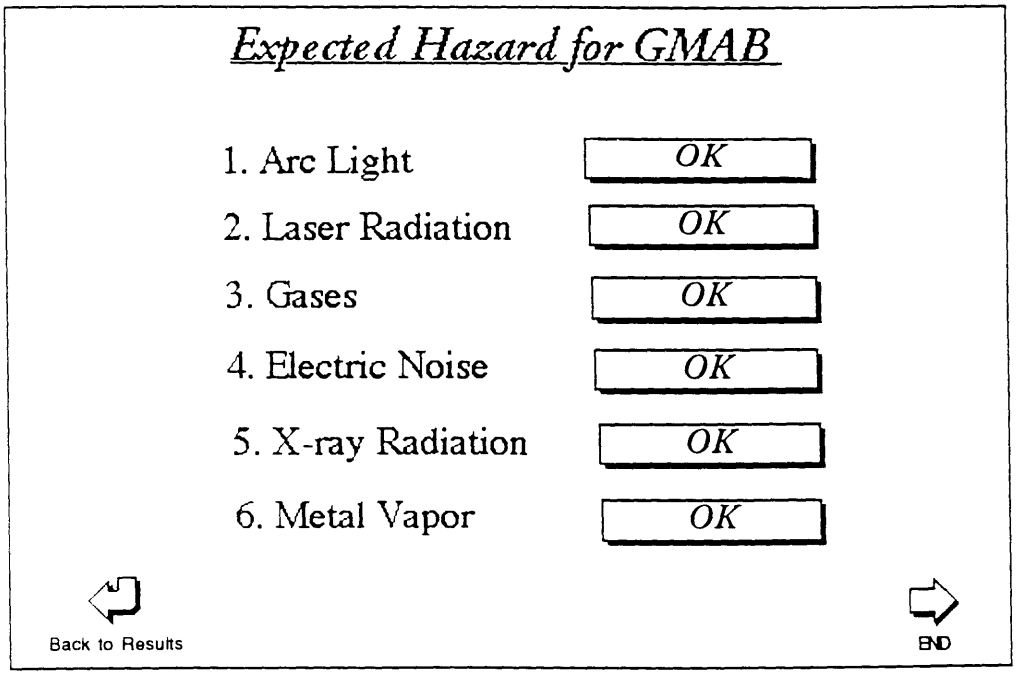

Expected Hazard for EBW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

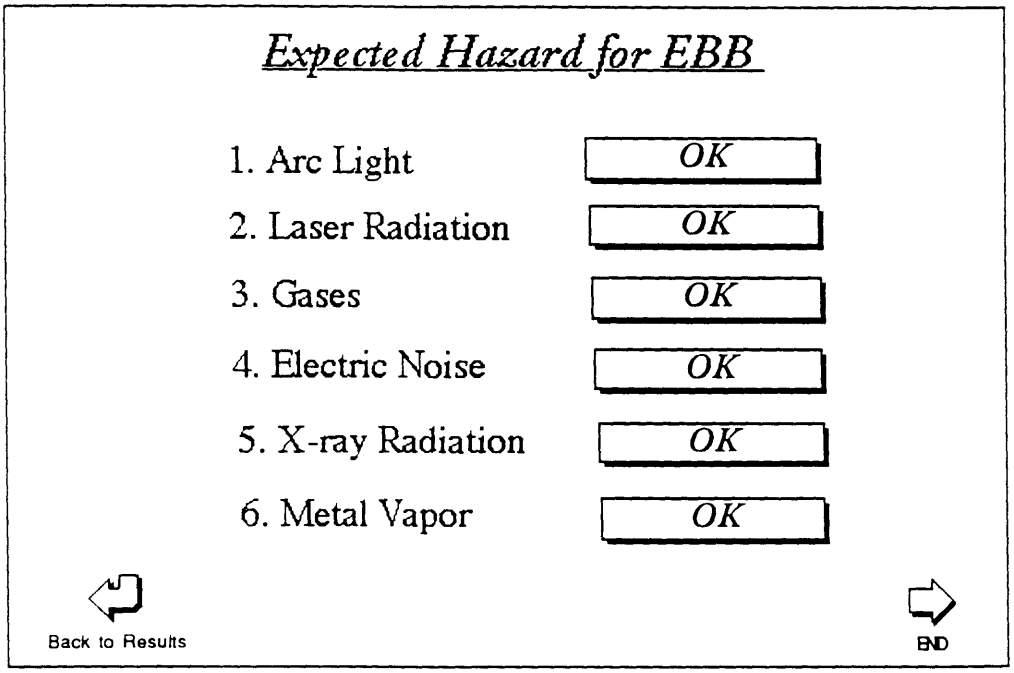

Expected Hazard for RW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

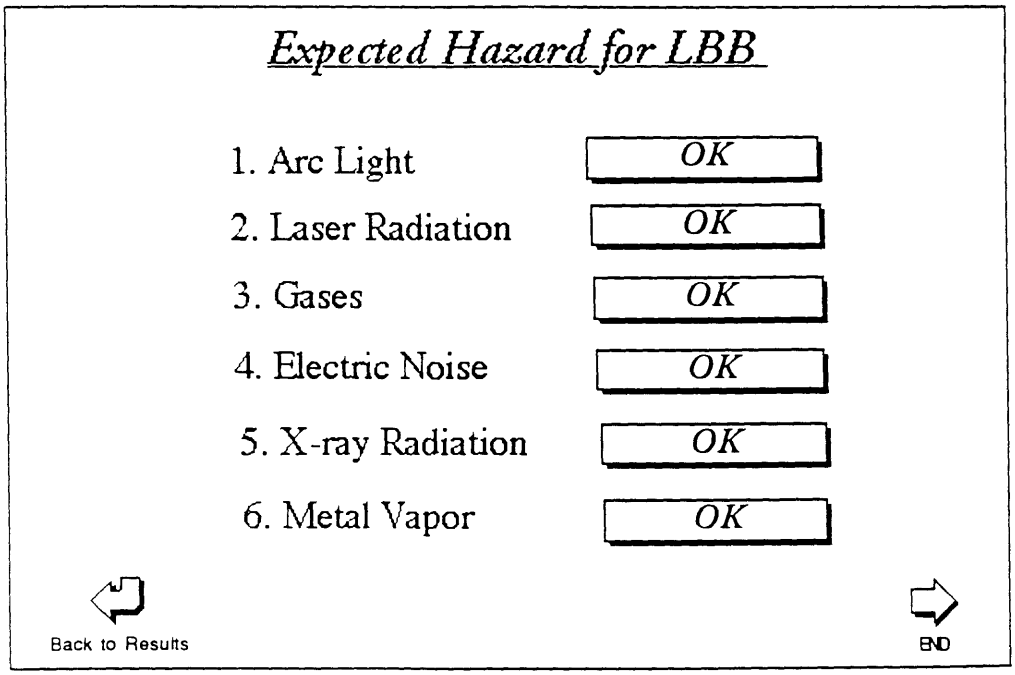

Expected Hazard for FW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END

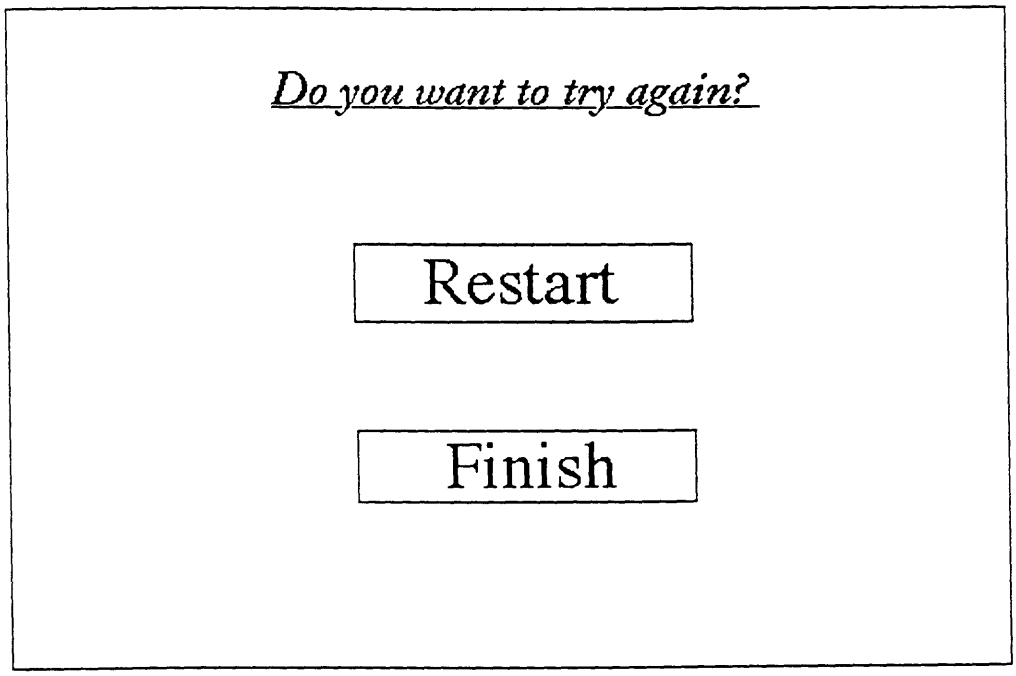

Expected Hazard for SW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END
Expected Hazard for TW
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END


Expected Hazard for GTAB
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END


Expected Hazard for GMAB
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END


Expected Hazard for EBB
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END


Expected Hazard for LBB
1. Arc Light
OK
2. Laser Radiation
OK
3. Gases
OK
4. Electric Noise
OK
5. X-ray Radiation
OK
6. Metal Vapor
OK
Back to Results
END


Do you want to try again?
Restart
Finish

Appendix B
Knowledge-Base (Rules)

Rule Main_rule_12 (#1)

If
EBB.material is not "not_available"
And EBB.thickness is not "not_available"
And EBB.joint_type is not "not_available"
And EBB.shape is not "not_available"
And EBB.welding_skill is not "Difficult"
And EBB.weld_type is not "not_available"
And EBB.power_capacity is not "not_available"
And EBB.micro_gravity is not "not_available"
And EBB.pressure is not "not_available"
And EBB.temperature is not "not_available"
And EBB.equipment_weight is not "too_heavy"
Then **EBB.availability**
is confirmed.

Rule Main_rule_5 (#2)

If
EBW.material is not "not_available"
And EBW.thickness is not "not_available"
And EBW.joint_type is not "not_available"
And EBW.shape is not "not_available"
And EBW.welding_skill is not "Difficult"
And EBW.weld_type is not "not_available"
And EBW.power_capacity is not "not_available"
And EBW.micro_gravity is not "not_available"
And EBW.pressure is not "not_available"
And EBW.temperature is not "not_available"
And EBW.equipment_weight is not "too_heavy"
Then **EBW.availability**
is confirmed.

Rule Main_rule_7 (#3)

If
FW.material is not "not_available"
And FW.thickness is not "not_available"
And FW.joint_type is not "not_available"
And FW.shape is not "not_available"
And FW.welding_skill is not "Difficult"
And FW.weld_type is not "not_available"
And FW.power_capacity is not "not_available"
And FW.micro_gravity is not "not_available"
And FW.pressure is not "not_available"
And FW.temperature is not "not_available"
And FW.equipment_weight is not "too_heavy"
Then **FW.availability**
is confirmed.

Rule Main_rule_11 (#4)

If
GMAB.material is not "not_available"
And GMAB.thickness is not "not_available"
And GMAB.joint_type is not "not_available"
And GMAB.shape is not "not_available"
And GMAB.welding_skill is not "Difficult"
And GMAB.weld_type is not "not_available"
And GMAB.power_capacity is not "not_available"
And GMAB.micro_gravity is not "not_available"
And GMAB.pressure is not "not_available"
And GMAB.temperature is not "not_available"
And GMAB.equipment_weight is not "too_heavy"
Then **GMAB.availability**
is confirmed.

Rule Main_rule_2 (#5)

If
GMAW.material is not "not_available"
And GMAW.thickness is not "not_available"
And GMAW.joint_type is not "not_available"
And GMAW.shape is not "not_available"
And GMAW.welding_skill is not "Difficult"
And GMAW.weld_type is not "not_available"
And GMAW.power_capacity is not "not_available"
And GMAW.micro_gravity is not "not_available"
And GMAW.pressure is not "not_available"
And GMAW.temperature is not "not_available"
And GMAW.equipment_weight is not "too_heavy"
Then **GMAW.availability**
is confirmed.

Rule Main_rule_10 (#6)

If
GTAB.material is not "not_available"
And GTAB.thickness is not "not_available"
And GTAB.joint_type is not "not_available"
And GTAB.shape is not "not_available"
And GTAB.welding_skill is not "Difficult"
And GTAB.weld_type is not "not_available"
And GTAB.power_capacity is not "not_available"
And GTAB.micro_gravity is not "not_available"
And GTAB.pressure is not "not_available"
And GTAB.temperature is not "not_available"
And GTAB.equipment_weight is not "too_heavy"
Then **GTAB.availability**
is confirmed.

Rule Main_rule_1 (#7)

```
If
 GTAW.material is not "not_available"
 And GTAW.thickness is not "not_available"
 And GTAW.joint_type is not "not_available"
 And GTAW.shape is not "not_available"
 And GTAW.welding_skill is not "Difficult"
 And GTAW.weld_type is not "not_available"
 And GTAW.power_capacity is not "not_available"
 And GTAW.micro_gravity is not "not_available"
 And GTAW.pressure is not "not_available"
 And GTAW.temperature is not "not_available"
 And GTAW.equipment_weight is not "too_heavy"
Then GTAW.availability
 is confirmed.

          Rule Main_rule_13 (#8)
If
 LBB.material is not "not_available"
 And LBB.thickness is not "not_available"
 And LBB.joint_type is not "not_available"
 And LBB.shape is not "not_available"
 And LBB.welding_skill is not "Difficult"
 And LBB.weld_type is not "not_available"
 And LBB.power_capacity is not "not_available"
 And LBB.micro_gravity is not "not_available"
 And LBB.pressure is not "not_available"
 And LBB.temperature is not "not_available"
 And LBB.equipment_weight is not "too_heavy"
Then LBB.availability
 is confirmed.

          Rule Main_rule_4 (#9)
If
 LBW.material is not "not_available"
 And LBW.thickness is not "not_available"
 And LBW.joint_type is not "not_available"
 And LBW.shape is not "not_available"
 And LBW.welding_skill is not "Difficult"
 And LBW.weld_type is not "not_available"
 And LBW.power_capacity is not "not_available"
 And LBW.micro_gravity is not "not_available"
 And LBW.pressure is not "not_available"
 And LBW.temperature is not "not_available"
 And LBW.equipment_weight is not "too_heavy"
Then LBW.availability
 is confirmed.

          Rule OK1 (#10)
If
```

```
test.pressure_data is greater than or equal to 0.0
And test.micro_gravity_data is greater than or equal to 0.0
And test.temperature_data is greater than or equal to 0.0
And test.weld_type is not "A"
And test.joint_type is not "A"
And test.material is not "A"
And test.shape is not "A"
And test.thickness_data is greater than or equal to 0.0
And test.power_capacity_data is greater than or equal to 0.0
And test.equipment_weight_data is greater than or equal to 0.0
And test.welding_skill is not "A"
Then OK1
is confirmed.

        Rule Main_rule_3 (#11)
If
PAW.material is not "not_available"
And PAW.thickness is not "not_available"
And PAW.joint_type is not "not_available"
And PAW.shape is not "not_available"
And PAW.welding_skill is not "Difficult"
And PAW.weld_type is not "not_available"
And PAW.power_capacity is not "not_available"
And PAW.micro_gravity is not "not_available"
And PAW.pressure is not "not_available"
And PAW.temperature is not "not_available"
And PAW.equipment_weight is not "too_heavy"
Then PAW.availability
is confirmed.

        Rule Main_rule_6 (#12)
If
RW.material is not "not_available"
And RW.thickness is not "not_available"
And RW.joint_type is not "not_available"
And RW.shape is not "not_available"
And RW.welding_skill is not "Difficult"
And RW.weld_type is not "not_available"
And RW.power_capacity is not "not_available"
And RW.micro_gravity is not "not_available"
And RW.pressure is not "not_available"
And RW.temperature is not "not_available"
And RW.equipment_weight is not "too_heavy"
Then RW.availability
is confirmed.

        Rule Main_rule_8 (#13)
If
SW.material is not "not_available"
```

```
And SW.thickness is not "not_available"
And SW.joint_type is not "not_available"
And SW.shape is not "not_available"
And SW.welding_skill is not "Difficult"
And SW.weld_type is not "not_available"
And SW.power_capacity is not "not_available"
And SW.micro_gravity is not "not_available"
And SW.pressure is not "not_available"
And SW.temperature is not "not_available"
And SW.equipment_weight is not "too_heavy"
Then SW.availability
is confirmed.

        Rule test_result_equipment_weight_EW1 (#14)
If
Retrieve "equipment_weight.slk" @TYPE=SYLK;
And test.equipment_weight_data-GTAW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW1
is confirmed.
And GTAW.equipment_weight is set to "suitable"

        Rule test_result_equipment_weight_EW10 (#15)
If
Retrieve "equipment_weight.slk" @TYPE=SYLK;
And test.equipment_weight_data-EBW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW10
is confirmed.
And EBW.equipment_weight is set to "too_heavy"

        Rule test_result_equipment_weight_EW11 (#16)
If
Retrieve "equipment_weight.slk" @TYPE=SYLK;
And test.equipment_weight_data-RW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW11
is confirmed.
And RW.equipment_weight is set to "suitable"

        Rule test_result_equipment_weight_EW12 (#17)
If
Retrieve "equipment_weight.slk" @TYPE=SYLK;
And test.equipment_weight_data-RW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW12
is confirmed.
And RW.equipment_weight is set to "too_heavy"

        Rule test_result_equipment_weight_EW13 (#18)
If
Retrieve "equipment_weight.slk" @TYPE=SYLK;
And test.equipment_weight_data-FW.equipment_weight_min is less than or equal to 0.0
```

```
Then test_result_equipment_weight.EW13
 is confirmed.
 And FW.equipment_weight is set to "suitable"

          Rule test_result_equipment_weight_EW14 (#19)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-FW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW14
 is confirmed.
 And FW.equipment_weight is set to "too_heavy"

          Rule test_result_equipment_weight_EW15 (#20)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-SW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW15
 is confirmed.
 And SW.equipment_weight is set to "suitable"

          Rule test_result_equipment_weight_EW16 (#21)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-SW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW16
 is confirmed.
 And SW.equipment_weight is set to "too_heavy"

          Rule test_result_equipment_weight_EW17 (#22)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-TW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW17
 is confirmed.
 And TW.equipment_weight is set to "suitable"

          Rule test_result_equipment_weight_EW18 (#23)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-TW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW18
 is confirmed.
 And TW.equipment_weight is set to "too_heavy"

          Rule test_result_equipment_weight_EW19 (#24)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GTAB.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW19
```

```
is confirmed.
And GTAB.equipment_weight is set to "suitable"

        Rule test_result_equipment_weight_EW2 (#25)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GTAW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW2
 is confirmed.
 And GTAW.equipment_weight is set to "too_heavy"

        Rule test_result_equipment_weight_EW20 (#26)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GTAB.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW20
 is confirmed.
 And GTAB.equipment_weight is set to "too_heavy"

        Rule test_result_equipment_weight_EW21 (#27)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GMAB.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW21
 is confirmed.
 And GMAB.equipment_weight is set to "suitable"

        Rule test_result_equipment_weight_EW22 (#28)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GMAB.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW22
 is confirmed.
 And GMAB.equipment_weight is set to "too_heavy"

        Rule test_result_equipment_weight_EW23 (#29)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-EBB.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW23
 is confirmed.
 And EBB.equipment_weight is set to "suitable"

        Rule test_result_equipment_weight_EW24 (#30)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-EBB.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW24
 is confirmed.
```

```
 And EBB.equipment_weight is set to "too_heavy"

         Rule test_result_equipment_weight_EW25 (#31)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-LBB.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW25
 is confirmed.
 And LBB.equipment_weight is set to "suitable"

         Rule test_result_equipment_weight_EW26 (#32)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-LBB.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW26
 is confirmed.
 And LBB.equipment_weight is set to "too_heavy"

         Rule test_result_equipment_weight_EW3 (#33)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GMAW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW3
 is confirmed.
 And GMAW.equipment_weight is set to "suitable"

         Rule test_result_equipment_weight_EW4 (#34)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-GMAW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW4
 is confirmed.
 And GMAW.equipment_weight is set to "too_heavy"

         Rule test_result_equipment_weight_EW5 (#35)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-PAW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW5
 is confirmed.
 And PAW.equipment_weight is set to "suitable"

         Rule test_result_equipment_weight_EW6 (#36)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-PAW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW6
 is confirmed.
 And PAW.equipment_weight is set to "too_heavy"
```

```
        Rule test_result_equipment_weight_EW7 (#37)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-LBW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW7
 is confirmed.
 And LBW.equipment_weight is set to "suitable"

        Rule test_result_equipment_weight_EW8 (#38)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-LBW.equipment_weight_min is greater than 0.0
Then test_result_equipment_weight.EW8
 is confirmed.
 And LBW.equipment_weight is set to "too_heavy"

        Rule test_result_equipment_weight_EW9 (#39)
If
 Retrieve "equipment_weight.slk" @TYPE=SYLK;
 And test.equipment_weight_data-EBW.equipment_weight_min is less than or equal to 0.0
Then test_result_equipment_weight.EW9
 is confirmed.
 And EBW.equipment_weight is set to "suitable"

        Rule test_result_hazard1 (#40)
If
 there is evidence of GTAW.availability
Then test_result_hazard.H1
 is confirmed.
 And GTAW.arc_light is set to TRUE
 And GTAW.laser_radiation is set to FALSE
 And GTAW.gases is set to TRUE
 And GTAW.electric_noise is set to TRUE
 And GTAW.Xray_radiation is set to FALSE
 And GTAW.metal_vapor is set to TRUE

        Rule test_result_hazard10 (#41)
If
 there is evidence of GTAB.availability
Then test_result_hazard.H10
 is confirmed.
 And GTAB.arc_light is set to TRUE
 And GTAB.laser_radiation is set to FALSE
 And GTAB.gases is set to TRUE
 And GTAB.electric_noise is set to TRUE
 And GTAB.Xray_radiation is set to FALSE
 And GTAB.metal_vapor is set to TRUE
```

Rule test_result_hazard11 (#42)

If
there is evidence of GMAB.availability
Then **test_result_hazard.H11**
is confirmed.
And GMAB.arc_light is set to TRUE
And GMAB.laser_radiation is set to FALSE
And GMAB.gases is set to TRUE
And GMAB.electric_noise is set to TRUE
And GMAB.Xray_radiation is set to FALSE
And GMAB.metal_vapor is set to TRUE

Rule test_result_hazard12 (#43)

If
there is evidence of EBB.availability
Then **test_result_hazard.H12**
is confirmed.
And EBB.arc_light is set to FALSE
And EBB.laser_radiation is set to FALSE
And EBB.gases is set to FALSE
And EBB.electric_noise is set to TRUE
And EBB.Xray_radiation is set to TRUE
And EBB.metal_vapor is set to TRUE

Rule test_result_hazard13 (#44)

If
there is evidence of LBB.availability
Then **test_result_hazard.H13**
is confirmed.
And LBB.arc_light is set to FALSE
And LBB.laser_radiation is set to TRUE
And LBB.gases is set to TRUE
And LBB.electric_noise is set to TRUE
And LBB.Xray_radiation is set to FALSE
And LBB.metal_vapor is set to TRUE

Rule test_result_hazard2 (#45)

If
there is evidence of GMAW.availability
Then **test_result_hazard.H2**
is confirmed.
And GMAW.arc_light is set to TRUE
And GMAW.laser_radiation is set to FALSE
And GMAW.gases is set to TRUE
And GMAW.electric_noise is set to TRUE
And GMAW.Xray_radiation is set to FALSE
And GMAW.metal_vapor is set to TRUE

Rule test_result_hazard3 (#46)

```
If
 there is evidence of PAW.availability
Then test_result_hazard.H3
 is confirmed.
 And PAW.arc_light is set to TRUE
 And PAW.laser_radiation is set to FALSE
 And PAW.gases is set to TRUE
 And PAW.electric_noise is set to TRUE
 And PAW.Xray_radiation is set to FALSE
 And PAW.metal_vapor is set to TRUE

          Rule test_result_hazard4 (#47)
If
 there is evidence of LBW.availability
Then test_result_hazard.H4
 is confirmed.
 And LBW.arc_light is set to FALSE
 And LBW.laser_radiation is set to TRUE
 And LBW.gases is set to TRUE
 And LBW.electric_noise is set to TRUE
 And LBW.Xray_radiation is set to FALSE
 And LBW.metal_vapor is set to TRUE

          Rule test_result_hazard5 (#48)
If
 there is evidence of EBW.availability
Then test_result_hazard.H5
 is confirmed.
 And EBW.arc_light is set to TRUE
 And EBW.laser_radiation is set to FALSE
 And EBW.gases is set to FALSE
 And EBW.electric_noise is set to TRUE
 And EBW.Xray_radiation is set to TRUE
 And EBW.metal_vapor is set to TRUE

          Rule test_result_hazard6 (#49)
If
 there is evidence of RW.availability
Then test_result_hazard.H6
 is confirmed.
 And RW.arc_light is set to FALSE
 And RW.laser_radiation is set to FALSE
 And RW.gases is set to FALSE
 And RW.electric_noise is set to TRUE
 And RW.Xray_radiation is set to FALSE
 And RW.metal_vapor is set to FALSE

          Rule test_result_hazard7 (#50)
If
```

there is evidence of FW.availability
Then **test_result_hazard.H7**
is confirmed.
And FW.arc_light is set to FALSE
And FW.laser_radiation is set to FALSE
And FW.gases is set to FALSE
And FW.electric_noise is set to TRUE
And FW.Xray_radiation is set to FALSE
And FW.metal_vapor is set to FALSE

Rule test_result_hazard8 (#51)
If
there is evidence of SW.availability
Then **test_result_hazard.H8**
is confirmed.
And SW.arc_light is set to TRUE
And SW.laser_radiation is set to FALSE
And SW.gases is set to FALSE
And SW.electric_noise is set to TRUE
And SW.Xray_radiation is set to FALSE
And SW.metal_vapor is set to TRUE

Rule test_result_hazard9 (#52)
If
there is evidence of TW.availability
Then **test_result_hazard.H9**
is confirmed.
And TW.arc_light is set to FALSE
And TW.laser_radiation is set to FALSE
And TW.gases is set to FALSE
And TW.electric_noise is set to FALSE
And TW.Xray_radiation is set to FALSE
And TW.metal_vapor is set to FALSE

Rule test_result_joint_type_1 (#53)
If
test.joint_type is "BUTT"
Then **test_result_joint_type.JT1**
is confirmed.
And GTAW.joint_type is set to "suitable"
And GMAW.joint_type is set to "suitable"
And PAW.joint_type is set to "suitable"
And LBW.joint_type is set to "suitable"
And EBW.joint_type is set to "suitable"
And RW.joint_type is set to "not_available"
And FW.joint_type is set to "suitable"
And SW.joint_type is set to "not_available"
And TW.joint_type is set to "suitable"
And GTAB.joint_type is set to "suitable"

```
 And GMAB.joint_type is set to "suitable"
 And EBB.joint_type is set to "suitable"
 And LBB.joint_type is set to "suitable"

          Rule test_result_joint_type_2 (#54)
If
 test.joint_type is "CORNER"
Then test_result_joint_type.JT2
 is confirmed.
 And GTAW.joint_type is set to "suitable"
 And GMAW.joint_type is set to "suitable"
 And PAW.joint_type is set to "suitable"
 And LBW.joint_type is set to "suitable"
 And EBW.joint_type is set to "suitable"
 And RW.joint_type is set to "not_available"
 And FW.joint_type is set to "not_available"
 And SW.joint_type is set to "not_available"
 And TW.joint_type is set to "not_available"
 And GTAB.joint_type is set to "suitable"
 And GMAB.joint_type is set to "suitable"
 And EBB.joint_type is set to "suitable"
 And LBB.joint_type is set to "suitable"

          Rule test_result_joint_type_3 (#55)
If
 test.joint_type is "LAP"
Then test_result_joint_type.JT3
 is confirmed.
 And GTAW.joint_type is set to "suitable"
 And GMAW.joint_type is set to "suitable"
 And PAW.joint_type is set to "suitable"
 And LBW.joint_type is set to "suitable"
 And EBW.joint_type is set to "suitable"
 And RW.joint_type is set to "suitable"
 And FW.joint_type is set to "not_available"
 And SW.joint_type is set to "not_available"
 And TW.joint_type is set to "not_available"
 And GTAB.joint_type is set to "suitable"
 And GMAB.joint_type is set to "suitable"
 And EBB.joint_type is set to "suitable"
 And LBB.joint_type is set to "suitable"

          Rule test_result_joint_type_4 (#56)
If
 test.joint_type is "EDGE"
Then test_result_joint_type.JT4
 is confirmed.
 And GTAW.joint_type is set to "suitable"
 And GMAW.joint_type is set to "suitable"
```

```
 And PAW.joint_type is set to "suitable"
 And LBW.joint_type is set to "suitable"
 And EBW.joint_type is set to "suitable"
 And RW.joint_type is set to "suitable"
 And FW.joint_type is set to "not_available"
 And SW.joint_type is set to "not_available"
 And TW.joint_type is set to "suitable"
 And GTAB.joint_type is set to "suitable"
 And GMAB.joint_type is set to "suitable"
 And EBB.joint_type is set to "suitable"
 And LBB.joint_type is set to "suitable"

          Rule test_result_joint_type_5 (#57)
If
 test.joint_type is "T"
Then test_result_joint_type.JT5
 is confirmed.
 And GTAW.joint_type is set to "suitable"
 And GMAW.joint_type is set to "suitable"
 And PAW.joint_type is set to "suitable"
 And LBW.joint_type is set to "suitable"
 And EBW.joint_type is set to "suitable"
 And RW.joint_type is set to "not_available"
 And FW.joint_type is set to "suitable"
 And SW.joint_type is set to "suitable"
 And TW.joint_type is set to "not_available"
 And GTAB.joint_type is set to "suitable"
 And GMAB.joint_type is set to "suitable"
 And EBB.joint_type is set to "suitable"
 And LBB.joint_type is set to "suitable"

          Rule test_result_material_2 (#58)
If
 test.material is "Aluminum"
Then test_result_material.Aluminum
 is confirmed.
 And GTAW.material is set to "suitable"
 And GMAW.material is set to "suitable"
 And PAW.material is set to "suitable"
 And LBW.material is set to "suitable"
 And EBW.material is set to "suitable"
 And RW.material is set to "suitable"
 And FW.material is set to "suitable"
 And SW.material is set to "suitable"
 And TW.material is set to "available"
 And GTAB.material is set to "suitable"
 And GMAB.material is set to "suitable"
 And EBB.material is set to "suitable"
 And LBB.material is set to "suitable"
```

Rule test_result_material_5 (#59)

If
test.material is "CC_Composite"
Then **test_result_material.CC_Composite**
is confirmed.
And GTAW.material is set to "not_available"
And GMAW.material is set to "not_available"
And PAW.material is set to "not_available"
And LBW.material is set to "not_available"
And EBW.material is set to "not_available"
And RW.material is set to "not_available"
And FW.material is set to "not_available"
And SW.material is set to "not_available"
And TW.material is set to "not_available"
And GTAB.material is set to "available"
And GMAB.material is set to "not_available"
And EBB.material is set to "available"
And LBB.material is set to "available"

Rule test_result_material_4 (#60)

If
test.material is "FRM"
Then **test_result_material.FRM**
is confirmed.
And GTAW.material is set to "not_available"
And GMAW.material is set to "not_available"
And PAW.material is set to "not_available"
And LBW.material is set to "not_available"
And EBW.material is set to "not_available"
And RW.material is set to "not_available"
And FW.material is set to "not_available"
And SW.material is set to "not_available"
And TW.material is set to "not_available"
And GTAB.material is set to "suitable"
And GMAB.material is set to "not_available"
And EBB.material is set to "suitable"
And LBB.material is set to "suitable"

Rule test_result_material_1 (#61)

If
test.material is "Steels"
Then **test_result_material.Steels**
is confirmed.
And GTAW.material is set to "suitable"
And GMAW.material is set to "suitable"
And PAW.material is set to "suitable"
And LBW.material is set to "suitable"
And EBW.material is set to "suitable"

```
And RW.material is set to "suitable"
And FW.material is set to "suitable"
And SW.material is set to "suitable"
And TW.material is set to "suitable"
And GTAB.material is set to "suitable"
And GMAB.material is set to "suitable"
And EBB.material is set to "suitable"
And LBB.material is set to "suitable"

        Rule test_result_material_3 (#62)
If
test.material is "Titanium"
Then test_result_material.Titanium
is confirmed.
And GTAW.material is set to "suitable"
And GMAW.material is set to "available"
And PAW.material is set to "suitable"
And LBW.material is set to "available"
And EBW.material is set to "suitable"
And RW.material is set to "suitable"
And FW.material is set to "available"
And SW.material is set to "available"
And TW.material is set to "not_available"
And GTAB.material is set to "suitable"
And GMAB.material is set to "suitable"
And EBB.material is set to "suitable"
And LBB.material is set to "suitable"

        Rule test_result_micro_gravity_MG1 (#63)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-GTAW.micro_gravity_min is greater than or equal to 0.0
And test.micro_gravity_data-GTAW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG1
is confirmed.
And GTAW.micro_gravity is set to "suitable"

        Rule test_result_micro_gravity_MG10_2 (#64)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-EBW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG10
is confirmed.
And EBW.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG10_1 (#65)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-EBW.micro_gravity_min is less than 0.0
```

```
Then test_result_micro_gravity.MG10
 is confirmed.
 And EBW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG11 (#66)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-RW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-RW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG11
 is confirmed.
 And RW.micro_gravity is set to "suitable"

          Rule test_result_micro_gravity_MG12_2 (#67)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-RW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG12
 is confirmed.
 And RW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG12_1 (#68)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-RW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG12
 is confirmed.
 And RW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG13 (#69)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-FW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-FW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG13
 is confirmed.
 And FW.micro_gravity is set to "suitable"

          Rule test_result_micro_gravity_MG14_2 (#70)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-FW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG14
 is confirmed.
 And FW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG14_1 (#71)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
```

```
 And test.micro_gravity_data-FW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG14
 is confirmed.
 And FW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG15 (#72)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-SW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-SW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG15
 is confirmed.
 And SW.micro_gravity is set to "suitable"

          Rule test_result_micro_gravity_MG16_2 (#73)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-SW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG16
 is confirmed.
 And SW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG16_1 (#74)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-SW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG16
 is confirmed.
 And SW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG17 (#75)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-TW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-TW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG17
 is confirmed.
 And TW.micro_gravity is set to "suitable"

          Rule test_result_micro_gravity_MG18_2 (#76)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-TW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG18
 is confirmed.
 And TW.micro_gravity is set to "not_available"

          Rule test_result_micro_gravity_MG18_1 (#77)
If
```

```
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-TW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG18
 is confirmed.
 And TW.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG19 (#78)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GTAB.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-GTAB.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG19
 is confirmed.
 And GTAB.micro_gravity is set to "suitable"

         Rule test_result_micro_gravity_MG2_2 (#79)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GTAW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG2
 is confirmed.
 And GTAW.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG2_1 (#80)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GTAW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG2
 is confirmed.
 And GTAW.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG20_2 (#81)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GTAB.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG20
 is confirmed.
 And GTAB.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG20_1 (#82)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GTAB.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG20
 is confirmed.
 And GTAB.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG21 (#83)
If
```

```
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-GMAB.micro_gravity_min is greater than or equal to 0.0
And test.micro_gravity_data-GMAB.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG21
is confirmed.
And GMAB.micro_gravity is set to "suitable"

        Rule test_result_micro_gravity_MG22_2 (#84)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-GMAB.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG22
is confirmed.
And GMAB.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG22_1 (#85)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-GMAB.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG22
is confirmed.
And GMAB.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG23 (#86)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-EBB.micro_gravity_min is greater than or equal to 0.0
And test.micro_gravity_data-EBB.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG23
is confirmed.
And EBB.micro_gravity is set to "suitable"

        Rule test_result_micro_gravity_MG24_2 (#87)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-EBB.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG24
is confirmed.
And EBB.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG24_1 (#88)
If
Retrieve "micro_gravity.slk" @TYPE=SYLK;
And test.micro_gravity_data-EBB.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG24
is confirmed.
And EBB.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG25 (#89)
```

```
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-LBB.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-LBB.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG25
 is confirmed.
 And LBB.micro_gravity is set to "suitable"

         Rule test_result_micro_gravity_MG26_2 (#90)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-LBB.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG26
 is confirmed.
 And LBB.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG26_1 (#91)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-LBB.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG26
 is confirmed.
 And LBB.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG3 (#92)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GMAW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-GMAW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG3
 is confirmed.
 And GMAW.micro_gravity is set to "suitable"

         Rule test_result_micro_gravity_MG4_2 (#93)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GMAW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG4
 is confirmed.
 And GMAW.micro_gravity is set to "not_available"

         Rule test_result_micro_gravity_MG4_1 (#94)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-GMAW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG4
 is confirmed.
 And GMAW.micro_gravity is set to "not_available"
```

```
        Rule test_result_micro_gravity_MG5 (#95)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-PAW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-PAW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG5
 is confirmed.
 And PAW.micro_gravity is set to "suitable"

        Rule test_result_micro_gravity_MG6_2 (#96)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-PAW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG6
 is confirmed.
 And PAW.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG6_1 (#97)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-PAW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG6
 is confirmed.
 And PAW.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG7 (#98)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-LBW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-LBW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG7
 is confirmed.
 And LBW.micro_gravity is set to "suitable"

        Rule test_result_micro_gravity_MG8_2 (#99)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-LBW.micro_gravity_max is greater than 0.0
Then test_result_micro_gravity.MG8
 is confirmed.
 And LBW.micro_gravity is set to "not_available"

        Rule test_result_micro_gravity_MG8_1 (#100)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-LBW.micro_gravity_min is less than 0.0
Then test_result_micro_gravity.MG8
 is confirmed.
 And LBW.micro_gravity is set to "not_available"
```

```
        Rule test_result_micro_gravity_MG9 (#101)
If
 Retrieve "micro_gravity.slk" @TYPE=SYLK;
 And test.micro_gravity_data-EBW.micro_gravity_min is greater than or equal to 0.0
 And test.micro_gravity_data-EBW.micro_gravity_max is less than or equal to 0.0
Then test_result_micro_gravity.MG9
 is confirmed.
 And EBW.micro_gravity is set to "suitable"

        Rule test_result_power_capacity_PC1 (#102)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GTAW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-GTAW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC1
 is confirmed.
 And GTAW.power_capacity is set to "suitable"

        Rule test_result_power_capacity_PC10_2 (#103)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-EBW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC10
 is confirmed.
 And EBW.power_capacity is set to "not_available"

        Rule test_result_power_capacity_PC10_1 (#104)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-EBW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC10
 is confirmed.
 And EBW.power_capacity is set to "not_available"

        Rule test_result_power_capacity_PC11 (#105)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-RW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-RW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC11
 is confirmed.
 And RW.power_capacity is set to "suitable"

        Rule test_result_power_capacity_PC12_2 (#106)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-RW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC12
```

```
is confirmed.
And RW.power_capacity is set to "not_available"

        Rule test_result_power_capacity_PC12_1 (#107)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-RW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC12
 is confirmed.
 And RW.power_capacity is set to "not_available"

        Rule test_result_power_capacity_PC13 (#108)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-FW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-FW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC13
 is confirmed.
 And FW.power_capacity is set to "suitable"

        Rule test_result_power_capacity_PC14_2 (#109)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-FW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC14
 is confirmed.
 And FW.power_capacity is set to "not_available"

        Rule test_result_power_capacity_PC14_1 (#110)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-FW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC14
 is confirmed.
 And FW.power_capacity is set to "not_available"

        Rule test_result_power_capacity_PC15 (#111)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-SW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-SW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC15
 is confirmed.
 And SW.power_capacity is set to "suitable"

        Rule test_result_power_capacity_PC16_2 (#112)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-SW.power_capacity_max is greater than 0.0
```

```
Then test_result_power_capacity.PC16
 is confirmed.
 And SW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC16_1 (#113)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-SW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC16
 is confirmed.
 And SW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC17 (#114)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-TW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-TW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC17
 is confirmed.
 And TW.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC18_2 (#115)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-TW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC18
 is confirmed.
 And TW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC18_1 (#116)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-TW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC18
 is confirmed.
 And TW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC19 (#117)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GTAB.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-GTAB.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC19
 is confirmed.
 And GTAB.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC2_2 (#118)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
```

```
 And test.power_capacity_data-GTAW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC2
 is confirmed.
 And GTAW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC2_1 (#119)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GTAW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC2
 is confirmed.
 And GTAW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC20_2 (#120)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GTAB.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC20
 is confirmed.
 And GTAB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC20_1 (#121)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GTAB.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC20
 is confirmed.
 And GTAB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC21 (#122)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GMAB.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-GMAB.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC21
 is confirmed.
 And GMAB.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC22_2 (#123)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GMAB.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC22
 is confirmed.
 And GMAB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC22_1 (#124)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
```

```
 And test.power_capacity_data-GMAB.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC22
 is confirmed.
 And GMAB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC23 (#125)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-EBB.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-EBB.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC23
 is confirmed.
 And EBB.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC24_2 (#126)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-EBB.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC24
 is confirmed.
 And EBB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC24_1 (#127)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-EBB.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC24
 is confirmed.
 And EBB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC25 (#128)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-LBB.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-LBB.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC25
 is confirmed.
 And LBB.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC26_2 (#129)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-LBB.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC26
 is confirmed.
 And LBB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC26_1 (#130)
If
```

```
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-LBB.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC26
 is confirmed.
 And LBB.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC3 (#131)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GMAW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-GMAW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC3
 is confirmed.
 And GMAW.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC4_2 (#132)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GMAW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC4
 is confirmed.
 And GMAW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC4_1 (#133)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-GMAW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC4
 is confirmed.
 And GMAW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC5 (#134)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-PAW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-PAW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC5
 is confirmed.
 And PAW.power_capacity is set to "suitable"

          Rule test_result_power_capacity_PC6_2 (#135)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-PAW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC6
 is confirmed.
 And PAW.power_capacity is set to "not_available"

          Rule test_result_power_capacity_PC6_1 (#136)
```

```
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-PAW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC6
 is confirmed.
 And PAW.power_capacity is set to "not_available"

         Rule test_result_power_capacity_PC7 (#137)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-LBW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-LBW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC7
 is confirmed.
 And LBW.power_capacity is set to "suitable"

         Rule test_result_power_capacity_PC8_2 (#138)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-LBW.power_capacity_max is greater than 0.0
Then test_result_power_capacity.PC8
 is confirmed.
 And LBW.power_capacity is set to "not_available"

         Rule test_result_power_capacity_PC8_1 (#139)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-LBW.power_capacity_min is less than 0.0
Then test_result_power_capacity.PC8
 is confirmed.
 And LBW.power_capacity is set to "not_available"

         Rule test_result_power_capacity_PC9 (#140)
If
 Retrieve "power_capacity.slk" @TYPE=SYLK;
 And test.power_capacity_data-EBW.power_capacity_min is greater than or equal to 0.0
 And test.power_capacity_data-EBW.power_capacity_max is less than or equal to 0.0
Then test_result_power_capacity.PC9
 is confirmed.
 And EBW.power_capacity is set to "suitable"

         Rule test_result_pressure_P1_1 (#141)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GTAW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-GTAW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P1
 is confirmed.
 And GTAW.pressure is set to "suitable"
```

```
        Rule test_result_pressure_P10_2 (#142)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-EBW.pressure_max is greater than 0.0
Then test_result_pressure.P10
 is confirmed.
 And EBW.pressure is set to "not_available"

        Rule test_result_pressure_P10_1 (#143)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-EBW.pressure_min is less than 0.0
Then test_result_pressure.P10
 is confirmed.
 And EBW.pressure is set to "not_available"

        Rule test_result_pressure_P11 (#144)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-RW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-RW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P11
 is confirmed.
 And RW.pressure is set to "suitable"

        Rule test_result_pressure_P12_2 (#145)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-RW.pressure_max is greater than 0.0
Then test_result_pressure.P12
 is confirmed.
 And RW.pressure is set to "not_available"

        Rule test_result_pressure_P12_1 (#146)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-RW.pressure_min is less than 0.0
Then test_result_pressure.P12
 is confirmed.
 And RW.pressure is set to "not_available"

        Rule test_result_pressure_P13 (#147)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-FW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-FW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P13
 is confirmed.
```

```
And FW.pressure is set to "suitable"

        Rule test_result_pressure_P14_2 (#148)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-FW.pressure_max is greater than 0.0
Then test_result_pressure.P14
 is confirmed.
 And FW.pressure is set to "not_available"

        Rule test_result_pressure_P14_1 (#149)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-FW.pressure_min is less than 0.0
Then test_result_pressure.P14
 is confirmed.
 And FW.pressure is set to "not_available"

        Rule test_result_pressure_P15 (#150)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-SW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-SW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P15
 is confirmed.
 And SW.pressure is set to "suitable"

        Rule test_result_pressure_P16_2 (#151)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-SW.pressure_max is greater than 0.0
Then test_result_pressure.P16
 is confirmed.
 And SW.pressure is set to "not_available"

        Rule test_result_pressure_P16_1 (#152)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-SW.pressure_min is less than 0.0
Then test_result_pressure.P16
 is confirmed.
 And SW.pressure is set to "not_available"

        Rule test_result_pressure_P17 (#153)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-TW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-TW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P17
```

```
is confirmed.
And TW.pressure is set to "suitable"

        Rule test_result_pressure_P18_2 (#154)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-TW.pressure_max is greater than 0.0
Then test_result_pressure.P18
 is confirmed.
 And TW.pressure is set to "not_available"

        Rule test_result_pressure_P18_1 (#155)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-TW.pressure_min is less than 0.0
Then test_result_pressure.P18
 is confirmed.
 And TW.pressure is set to "not_available"

        Rule test_result_pressure_P19 (#156)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GTAB.pressure_min is greater than or equal to 0.0
 And test.pressure_data-GTAB.pressure_max is less than or equal to 0.0
Then test_result_pressure.P19
 is confirmed.
 And GTAB.pressure is set to "suitable"

        Rule test_result_pressure_P2_2 (#157)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GTAW.pressure_max is greater than 0.0
Then test_result_pressure.P2
 is confirmed.
 And GTAW.pressure is set to "not_available"

        Rule test_result_pressure_P2_1 (#158)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GTAW.pressure_min is less than 0.0
Then test_result_pressure.P2
 is confirmed.
 And GTAW.pressure is set to "not_available"

        Rule test_result_pressure_P20_2 (#159)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GTAB.pressure_max is greater than 0.0
Then test_result_pressure.P20
```

```
is confirmed.
And GTAB.pressure is set to "not_available"

        Rule test_result_pressure_P20_1 (#160)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GTAB.pressure_min is less than 0.0
Then test_result_pressure.P20
 is confirmed.
 And GTAB.pressure is set to "not_available"

        Rule test_result_pressure_P21 (#161)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GMAB.pressure_min is greater than or equal to 0.0
 And test.pressure_data-GMAB.pressure_max is less than or equal to 0.0
Then test_result_pressure.P21
 is confirmed.
 And GMAB.pressure is set to "suitable"

        Rule test_result_pressure_P22_2 (#162)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GMAB.pressure_max is greater than 0.0
Then test_result_pressure.P22
 is confirmed.
 And GMAB.pressure is set to "not_available"

        Rule test_result_pressure_P22_1 (#163)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GMAB.pressure_min is less than 0.0
Then test_result_pressure.P22
 is confirmed.
 And GMAB.pressure is set to "not_available"

        Rule test_result_pressure_P23 (#164)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-EBB.pressure_min is greater than or equal to 0.0
 And test.pressure_data-EBB.pressure_max is less than or equal to 0.0
Then test_result_pressure.P23
 is confirmed.
 And EBB.pressure is set to "suitable"

        Rule test_result_pressure_P24_2 (#165)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-EBB.pressure_max is greater than 0.0
```

```
Then test_result_pressure.P24
 is confirmed.
 And EBB.pressure is set to "not_available"

          Rule test_result_pressure_P24_1 (#166)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-EBB.pressure_min is less than 0.0
Then test_result_pressure.P24
 is confirmed.
 And EBB.pressure is set to "not_available"

          Rule test_result_pressure_P25 (#167)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-LBB.pressure_min is greater than or equal to 0.0
 And test.pressure_data-LBB.pressure_max is less than or equal to 0.0
Then test_result_pressure.P25
 is confirmed.
 And LBB.pressure is set to "suitable"

          Rule test_result_pressure_P26_2 (#168)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-LBB.pressure_max is greater than 0.0
Then test_result_pressure.P26
 is confirmed.
 And LBB.pressure is set to "not_available"

          Rule test_result_pressure_P26_1 (#169)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-LBB.pressure_min is less than 0.0
Then test_result_pressure.P26
 is confirmed.
 And LBB.pressure is set to "not_available"

          Rule test_result_pressure_P3 (#170)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-GMAW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-GMAW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P3
 is confirmed.
 And GMAW.pressure is set to "suitable"

          Rule test_result_pressure_P4_2 (#171)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
```

```
 And test.pressure_data-GMAW.pressure_max is greater than 0.0
Then test_result_pressure.P4
 is confirmed.
 And GMAW.pressure is set to "not_available"

          Rule test_result_pressure_P4_1 (#172)
If
 Retrieve "pressure.slk" @TYPE=SYLK:
 And test.pressure_data-GMAW.pressure_min is less than 0.0
Then test_result_pressure.P4
 is confirmed.
 And GMAW.pressure is set to "not_available"

          Rule test_result_pressure_P5 (#173)
If
 Retrieve "pressure.slk" @TYPE=SYLK:
 And test.pressure_data-PAW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-PAW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P5
 is confirmed.
 And PAW.pressure is set to "suitable"

          Rule test_result_pressure_P6_2 (#174)
If
 Retrieve "pressure.slk" @TYPE=SYLK:
 And test.pressure_data-PAW.pressure_max is greater than 0.0
Then test_result_pressure.P6
 is confirmed.
 And PAW.pressure is set to "not_available"

          Rule test_result_pressure_P6_1 (#175)
If
 Retrieve "pressure.slk" @TYPE=SYLK:
 And test.pressure_data-PAW.pressure_min is less than 0.0
Then test_result_pressure.P6
 is confirmed.
 And PAW.pressure is set to "not_available"

          Rule test_result_pressure_P7 (#176)
If
 Retrieve "pressure.slk" @TYPE=SYLK:
 And test.pressure_data-LBW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-LBW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P7
 is confirmed.
 And LBW.pressure is set to "suitable"

          Rule test_result_pressure_P8_2 (#177)
If
```

```
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-LBW.pressure_max is greater than 0.0
Then test_result_pressure.P8
 is confirmed.
 And LBW.pressure is set to "not_available"

          Rule test_result_pressure_P8_1 (#178)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-LBW.pressure_min is less than 0.0
Then test_result_pressure.P8
 is confirmed.
 And LBW.pressure is set to "not_available"

          Rule test_result_pressure_P9 (#179)
If
 Retrieve "pressure.slk" @TYPE=SYLK;
 And test.pressure_data-EBW.pressure_min is greater than or equal to 0.0
 And test.pressure_data-EBW.pressure_max is less than or equal to 0.0
Then test_result_pressure.P9
 is confirmed.
 And EBW.pressure is set to "suitable"

          Rule test_result_shape_PipeBar_PipeBar (#180)
If
 test.shape is "PipeBar_PipeBar"
Then test_result_shape.PipeBar_PipeBar
 is confirmed.
 And GTAW.shape is set to "suitable"
 And GMAW.shape is set to "suitable"
 And PAW.shape is set to "suitable"
 And LBW.shape is set to "suitable"
 And EBW.shape is set to "suitable"
 And RW.shape is set to "not_available"
 And FW.shape is set to "suitable"
 And SW.shape is set to "not_available"
 And TW.shape is set to "suitable"
 And GTAB.shape is set to "suitable"
 And GMAB.shape is set to "suitable"
 And EBB.shape is set to "suitable"
 And LBB.shape is set to "suitable"

          Rule test_result_shape_PipeBar_Plate (#181)
If
 test.shape is "PipeBar_Plate"
Then test_result_shape.PipeBar_Plate
 is confirmed.
 And GTAW.shape is set to "suitable"
 And GMAW.shape is set to "suitable"
```

```
And PAW.shape is set to "suitable"
And LBW.shape is set to "suitable"
And EBW.shape is set to "suitable"
And RW.shape is set to "not_available"
And FW.shape is set to "suitable"
And SW.shape is set to "suitable"
And TW.shape is set to "suitable"
And GTAB.shape is set to "suitable"
And GMAB.shape is set to "suitable"
And EBB.shape is set to "suitable"
And LBB.shape is set to "suitable"

        Rule test_result_shape_Plate_Plate (#182)
If
 test.shape is "Plate_Plate"
Then test_result_shape.Plate_Plate
 is confirmed.
 And GTAW.shape is set to "suitable"
 And GMAW.shape is set to "suitable"
 And PAW.shape is set to "suitable"
 And LBW.shape is set to "suitable"
 And EBW.shape is set to "suitable"
 And RW.shape is set to "suitable"
 And FW.shape is set to "not_available"
 And SW.shape is set to "not_available"
 And TW.shape is set to "suitable"
 And GTAB.shape is set to "suitable"
 And GMAB.shape is set to "suitable"
 And EBB.shape is set to "suitable"
 And LBB.shape is set to "suitable"

        Rule test_result_temperature_T1 (#183)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GTAW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-GTAW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T1
 is confirmed.
 And GTAW.temperature is set to "suitable"

        Rule test_result_temperature_T10_2 (#184)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-EBW.temperature_max is greater than 0.0
Then test_result_temperature.T10
 is confirmed.
 And EBW.temperature is set to "not_available"

        Rule test_result_temperature_T10_1 (#185)
```

```
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-EBW.temperature_min is less than 0.0
Then test_result_temperature.T10
 is confirmed.
 And EBW.temperature is set to "not_available"

         Rule test_result_temperature_T11 (#186)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-RW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-RW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T11
 is confirmed.
 And RW.temperature is set to "suitable"

         Rule test_result_temperature_T12_2 (#187)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-RW.temperature_max is greater than 0.0
Then test_result_temperature.T12
 is confirmed.
 And RW.temperature is set to "not_available"

         Rule test_result_temperature_T12_1 (#188)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-RW.temperature_min is less than 0.0
Then test_result_temperature.T12
 is confirmed.
 And RW.temperature is set to "not_available"

         Rule test_result_temperature_T13 (#189)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-FW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-FW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T13
 is confirmed.
 And FW.temperature is set to "suitable"

         Rule test_result_temperature_T14_2 (#190)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-FW.temperature_max is greater than 0.0
Then test_result_temperature.T14
 is confirmed.
 And FW.temperature is set to "not_available"
```

```
        Rule test_result_temperature_T14_1 (#191)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-FW.temperature_min is less than 0.0
Then test_result_temperature.T14
 is confirmed.
 And FW.temperature is set to "not_available"

        Rule test_result_temperature_T15 (#192)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-SW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-SW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T15
 is confirmed.
 And SW.temperature is set to "suitable"

        Rule test_result_temperature_T16_2 (#193)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-SW.temperature_max is greater than 0.0
Then test_result_temperature.T16
 is confirmed.
 And SW.temperature is set to "not_available"

        Rule test_result_temperature_T16_1 (#194)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-SW.temperature_min is less than 0.0
Then test_result_temperature.T16
 is confirmed.
 And SW.temperature is set to "not_available"

        Rule test_result_temperature_T17 (#195)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-TW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-TW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T17
 is confirmed.
 And TW.temperature is set to "suitable"

        Rule test_result_temperature_T18_2 (#196)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-TW.temperature_max is greater than 0.0
Then test_result_temperature.T18
 is confirmed.
 And TW.temperature is set to "not_available"
```

```
        Rule test_result_temperature_T18_1 (#197)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-TW.temperature_min is less than 0.0
Then test_result_temperature.T18
 is confirmed.
 And TW.temperature is set to "not_available"

        Rule test_result_temperature_T19 (#198)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GTAB.temperature_min is greater than or equal to 0.0
 And test.temperature_data-GTAB.temperature_max is less than or equal to 0.0
Then test_result_temperature.T19
 is confirmed.
 And GTAB.temperature is set to "suitable"

        Rule test_result_temperature_T2_2 (#199)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GTAW.temperature_max is greater than 0.0
Then test_result_temperature.T2
 is confirmed.
 And GTAW.temperature is set to "not_available"

        Rule test_result_temperature_T2_1 (#200)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GTAW.temperature_min is less than 0.0
Then test_result_temperature.T2
 is confirmed.
 And GTAW.temperature is set to "not_available"

        Rule test_result_temperature_T20_2 (#201)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GTAB.temperature_max is greater than 0.0
Then test_result_temperature.T20
 is confirmed.
 And GTAB.temperature is set to "not_available"

        Rule test_result_temperature_T20_1 (#202)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GTAB.temperature_min is less than 0.0
Then test_result_temperature.T20
 is confirmed.
 And GTAB.temperature is set to "not_available"
```

```
        Rule test_result_temperature_T21 (#203)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GMAB.temperature_min is greater than or equal to 0.0
 And test.temperature_data-GMAB.temperature_max is less than or equal to 0.0
Then test_result_temperature.T21
 is confirmed.
 And GMAB.temperature is set to "suitable"

        Rule test_result_temperature_T22_2 (#204)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GMAB.temperature_max is greater than 0.0
Then test_result_temperature.T22
 is confirmed.
 And GMAB.temperature is set to "not_available"

        Rule test_result_temperature_T22_1 (#205)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GMAB.temperature_min is less than 0.0
Then test_result_temperature.T22
 is confirmed.
 And GMAB.temperature is set to "not_available"

        Rule test_result_temperature_T23 (#206)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-EBB.temperature_min is greater than or equal to 0.0
 And test.temperature_data-EBB.temperature_max is less than or equal to 0.0
Then test_result_temperature.T23
 is confirmed.
 And EBB.temperature is set to "suitable"

        Rule test_result_temperature_T24_2 (#207)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-EBB.temperature_max is greater than 0.0
Then test_result_temperature.T24
 is confirmed.
 And EBB.temperature is set to "not_available"

        Rule test_result_temperature_T24_1 (#208)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-EBB.temperature_min is less than 0.0
Then test_result_temperature.T24
 is confirmed.
```

```
 And EBB.temperature is set to "not_available"

          Rule test_result_temperature_T25 (#209)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-LBB.temperature_min is greater than or equal to 0.0
 And test.temperature_data-LBB.temperature_max is less than or equal to 0.0
Then test_result_temperature.T25
 is confirmed.
 And LBB.temperature is set to "suitable"

          Rule test_result_temperature_T26_2 (#210)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-LBB.temperature_max is greater than 0.0
Then test_result_temperature.T26
 is confirmed.
 And LBB.temperature is set to "not_available"

          Rule test_result_temperature_T26_1 (#211)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-LBB.temperature_min is less than 0.0
Then test_result_temperature.T26
 is confirmed.
 And LBB.temperature is set to "not_available"

          Rule test_result_temperature_T3 (#212)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GMAW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-GMAW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T3
 is confirmed.
 And GMAW.temperature is set to "suitable"

          Rule test_result_temperature_T4_2 (#213)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GMAW.temperature_max is greater than 0.0
Then test_result_temperature.T4
 is confirmed.
 And GMAW.temperature is set to "not_available"

          Rule test_result_temperature_T4_1 (#214)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-GMAW.temperature_min is less than 0.0
Then test_result_temperature.T4
```

```
 is confirmed.
 And GMAW.temperature is set to "not_available"

          Rule test_result_temperature_T5 (#215)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-PAW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-PAW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T5
 is confirmed.
 And PAW.temperature is set to "suitable"

          Rule test_result_temperature_T6_2 (#216)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-PAW.temperature_max is greater than 0.0
Then test_result_temperature.T6
 is confirmed.
 And PAW.temperature is set to "not_available"

          Rule test_result_temperature_T6_1 (#217)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-PAW.temperature_min is less than 0.0
Then test_result_temperature.T6
 is confirmed.
 And PAW.temperature is set to "not_available"

          Rule test_result_temperature_T7 (#218)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-LBW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-LBW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T7
 is confirmed.
 And LBW.temperature is set to "suitable"

          Rule test_result_temperature_T8_2 (#219)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-LBW.temperature_max is greater than 0.0
Then test_result_temperature.T8
 is confirmed.
 And LBW.temperature is set to "not_available"

          Rule test_result_temperature_T8_1 (#220)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-LBW.temperature_min is less than 0.0
```

```
Then test_result_temperature.T8
 is confirmed.
 And LBW.temperature is set to "not_available"

          Rule test_result_temperature_T9 (#221)
If
 Retrieve "temperature.slk" @TYPE=SYLK;
 And test.temperature_data-EBW.temperature_min is greater than or equal to 0.0
 And test.temperature_data-EBW.temperature_max is less than or equal to 0.0
Then test_result_temperature.T9
 is confirmed.
 And EBW.temperature is set to "suitable"

          Rule test_result_thickness_1 (#222)
If
 test.thickness_data is less than or equal to 4.0
Then test_result_thickness.T1
 is confirmed.
 And GTAW.thickness is set to "suitable"
 And GMAW.thickness is set to "suitable"
 And PAW.thickness is set to "suitable"
 And LBW.thickness is set to "suitable"
 And EBW.thickness is set to "suitable"
 And RW.thickness is set to "suitable"
 And FW.thickness is set to "suitable"
 And SW.thickness is set to "suitable"
 And TW.thickness is set to "suitable"
 And GTAB.thickness is set to "suitable"
 And GMAB.thickness is set to "suitable"
 And EBB.thickness is set to "suitable"
 And LBB.thickness is set to "suitable"

          Rule test_result_thickness_2 (#223)
If
 test.thickness_data is greater than 4.0
 And test.thickness_data is less than or equal to 10.0
Then test_result_thickness.T2
 is confirmed.
 And GTAW.thickness is set to "suitable"
 And GMAW.thickness is set to "suitable"
 And PAW.thickness is set to "suitable"
 And LBW.thickness is set to "suitable"
 And EBW.thickness is set to "suitable"
 And RW.thickness is set to "not_available"
 And FW.thickness is set to "suitable"
 And SW.thickness is set to "suitable"
 And TW.thickness is set to "suitable"
 And GTAB.thickness is set to "not_available"
 And GMAB.thickness is set to "not_available"
```

```
 And EBB.thickness is set to "not_available"
 And LBB.thickness is set to "not_available"

          Rule test_result_thickness_3 (#224)
If
 test.thickness_data is greater than 10.0
Then test_result_thickness.T3
 is confirmed.
 And GTAW.thickness is set to "suitable"
 And GMAW.thickness is set to "suitable"
 And PAW.thickness is set to "not_available"
 And LBW.thickness is set to "not_available"
 And EBW.thickness is set to "suitable"
 And RW.thickness is set to "not_available"
 And FW.thickness is set to "suitable"
 And SW.thickness is set to "not_available"
 And TW.thickness is set to "not_available"
 And GTAB.thickness is set to "not_available"
 And GMAB.thickness is set to "not_available"
 And EBB.thickness is set to "not_available"
 And LBB.thickness is set to "not_available"

          Rule test_result_weld_type_F1 (#225)
If
 test.joint_type is "LAP","CORNER","T"
 And test.weld_type is "F"
Then test_result_weld_type.F1
 is confirmed.
 And GTAW.weld_type is set to "suitable"
 And GMAW.weld_type is set to "suitable"
 And PAW.weld_type is set to "suitable"
 And LBW.weld_type is set to "suitable"
 And EBW.weld_type is set to "suitable"
 And RW.weld_type is set to "suitable"
 And FW.weld_type is set to "suitable"
 And SW.weld_type is set to "suitable"
 And TW.weld_type is set to "suitable"
 And GTAB.weld_type is set to "suitable"
 And GMAB.weld_type is set to "suitable"
 And EBB.weld_type is set to "suitable"
 And LBB.weld_type is set to "suitable"

          Rule test_result_weld_type_F2 (#226)
If
 test.joint_type is "BUTT","EDGE"
 And test.weld_type is "F"
Then test_result_weld_type.F2
 is confirmed.
 And GTAW.weld_type is set to "not_available"
```

And GMAW.weld_type is set to "not_available"
And PAW.weld_type is set to "not_available"
And LBW.weld_type is set to "not_available"
And EBW.weld_type is set to "not_available"
And RW.weld_type is set to "not_available"
And FW.weld_type is set to "not_available"
And SW.weld_type is set to "not_available"
And TW.weld_type is set to "not_available"
And GTAB.weld_type is set to "not_available"
And GMAB.weld_type is set to "not_available"
And EBB.weld_type is set to "not_available"
And LBB.weld_type is set to "not_available"

Rule test_result_weld_type_G1 (#227)

If
test.joint_type is "BUTT","CORNER","T","EDGE"
And test.weld_type is "G"
Then **test_result_weld_type.G1**
is confirmed.
And GTAW.weld_type is set to "suitable"
And GMAW.weld_type is set to "suitable"
And PAW.weld_type is set to "suitable"
And LBW.weld_type is set to "suitable"
And EBW.weld_type is set to "suitable"
And RW.weld_type is set to "suitable"
And FW.weld_type is set to "suitable"
And SW.weld_type is set to "suitable"
And TW.weld_type is set to "suitable"
And GTAB.weld_type is set to "suitable"
And GMAB.weld_type is set to "suitable"
And EBB.weld_type is set to "suitable"
And LBB.weld_type is set to "suitable"

Rule test_result_weld_type_G2 (#228)

If
test.joint_type is "LAP"
And test.weld_type is "G"
Then **test_result_weld_type.G2**
is confirmed.
And GTAW.weld_type is set to "not_available"
And GMAW.weld_type is set to "not_available"
And PAW.weld_type is set to "not_available"
And LBW.weld_type is set to "not_available"
And EBW.weld_type is set to "not_available"
And RW.weld_type is set to "not_available"
And FW.weld_type is set to "not_available"
And SW.weld_type is set to "not_available"
And TW.weld_type is set to "not_available"
And GTAB.weld_type is set to "not_available"

```
 And GMAB.weld_type is set to "not_available"
 And EBB.weld_type is set to "not_available"
 And LBB.weld_type is set to "not_available"

         Rule test_result_weld_type_I1 (#229)
If
 test.joint_type is "BUTT","CORNER","T","EDGE"
 And test.weld_type is "I"
Then test_result_weld_type.I1
 is confirmed.
 And GTAW.weld_type is set to "suitable"
 And GMAW.weld_type is set to "suitable"
 And PAW.weld_type is set to "suitable"
 And LBW.weld_type is set to "suitable"
 And EBW.weld_type is set to "suitable"
 And RW.weld_type is set to "suitable"
 And FW.weld_type is set to "suitable"
 And SW.weld_type is set to "suitable"
 And TW.weld_type is set to "suitable"
 And GTAB.weld_type is set to "suitable"
 And GMAB.weld_type is set to "suitable"
 And EBB.weld_type is set to "suitable"
 And LBB.weld_type is set to "suitable"

         Rule test_result_weld_type_I2 (#230)
If
 test.joint_type is "LAP"
 And test.weld_type is "I"
Then test_result_weld_type.I2
 is confirmed.
 And GTAW.weld_type is set to "not_available"
 And GMAW.weld_type is set to "not_available"
 And PAW.weld_type is set to "not_available"
 And LBW.weld_type is set to "not_available"
 And EBW.weld_type is set to "not_available"
 And RW.weld_type is set to "not_available"
 And FW.weld_type is set to "not_available"
 And SW.weld_type is set to "not_available"
 And TW.weld_type is set to "not_available"
 And GTAB.weld_type is set to "not_available"
 And GMAB.weld_type is set to "not_available"
 And EBB.weld_type is set to "not_available"
 And LBB.weld_type is set to "not_available"

         Rule test_result_weld_type_S1 (#231)
If
 test.joint_type is "LAP","CORNER","T","EDGE"
 And test.weld_type is "S"
Then test_result_weld_type.S1
```

```
is confirmed.
And GTAW.weld_type is set to "suitable"
And GMAW.weld_type is set to "suitable"
And PAW.weld_type is set to "suitable"
And LBW.weld_type is set to "suitable"
And EBW.weld_type is set to "suitable"
And RW.weld_type is set to "suitable"
And FW.weld_type is set to "suitable"
And SW.weld_type is set to "suitable"
And TW.weld_type is set to "suitable"
And GTAB.weld_type is set to "suitable"
And GMAB.weld_type is set to "suitable"
And EBB.weld_type is set to "suitable"
And LBB.weld_type is set to "suitable"

        Rule test_result_weld_type_S2 (#232)
If
 test.joint_type is "BUTT"
 And test.weld_type is "S"
Then test_result_weld_type.S2
 is confirmed.
 And GTAW.weld_type is set to "not_available"
 And GMAW.weld_type is set to "not_available"
 And PAW.weld_type is set to "not_available"
 And LBW.weld_type is set to "not_available"
 And EBW.weld_type is set to "not_available"
 And RW.weld_type is set to "not_available"
 And FW.weld_type is set to "not_available"
 And SW.weld_type is set to "not_available"
 And TW.weld_type is set to "not_available"
 And GTAB.weld_type is set to "not_available"
 And GMAB.weld_type is set to "not_available"
 And EBB.weld_type is set to "not_available"
 And LBB.weld_type is set to "not_available"

        Rule test_result_welding_skill_Expert (#233)
If
 test.welding_skill is "Expert"
Then test_result_welding_skill.Expert
 is confirmed.
 And GTAW.welding_skill is set to "Fair"
 And GMAW.welding_skill is set to "Fair"
 And PAW.welding_skill is set to "Fair"
 And LBW.welding_skill is set to "Fair"
 And EBW.welding_skill is set to "Fair"
 And RW.welding_skill is set to "Well_Done"
 And FW.welding_skill is set to "Well_Done"
 And SW.welding_skill is set to "Well_Done"
 And TW.welding_skill is set to "Well_Done"
```

```
 And GTAB.welding_skill is set to "Fair"
 And GMAB.welding_skill is set to "Fair"
 And EBB.welding_skill is set to "Fair"
 And LBB.welding_skill is set to "Fair"

          Rule test_result_welding_skill_Intermediate (#234)
If
 test.welding_skill is "Intermediate"
Then test_result_welding_skill.Intermediate
 is confirmed.
 And GTAW.welding_skill is set to "Difficult"
 And GMAW.welding_skill is set to "Difficult"
 And PAW.welding_skill is set to "Difficult"
 And LBW.welding_skill is set to "Difficult"
 And EBW.welding_skill is set to "Difficult"
 And RW.welding_skill is set to "Fair"
 And FW.welding_skill is set to "Fair"
 And SW.welding_skill is set to "Fair"
 And TW.welding_skill is set to "Fair"
 And GTAB.welding_skill is set to "Difficult"
 And GMAB.welding_skill is set to "Difficult"
 And EBB.welding_skill is set to "Difficult"
 And LBB.welding_skill is set to "Difficult"

          Rule test_result_welding_skill_Novice (#235)
If
 test.welding_skill is "Novice"
Then test_result_welding_skill.Novice
 is confirmed.
 And GTAW.welding_skill is set to "Difficult"
 And GMAW.welding_skill is set to "Difficult"
 And PAW.welding_skill is set to "Difficult"
 And LBW.welding_skill is set to "Difficult"
 And EBW.welding_skill is set to "Difficult"
 And RW.welding_skill is set to "Difficult"
 And FW.welding_skill is set to "Difficult"
 And SW.welding_skill is set to "Difficult"
 And TW.welding_skill is set to "Difficult"
 And GTAB.welding_skill is set to "Difficult"
 And GMAB.welding_skill is set to "Difficult"
 And EBB.welding_skill is set to "Difficult"
 And LBB.welding_skill is set to "Difficult"

          Rule Main_rule_9 (#236)
If
 TW.material is not "not_available"
 And TW.thickness is not "not_available"
 And TW.joint_type is not "not_available"
 And TW.shape is not "not_available"
```

And TW.welding_skill is not "Difficult"
And TW.weld_type is not "not_available"
And TW.power_capacity is not "not_available"
And TW.micro_gravity is not "not_available"
And TW.pressure is not "not_available"
And TW.temperature is not "not_available"
And TW.equipment_weight is not "too_heavy"
Then **TW.availability**
is confirmed.

Appendix C
Numerical Data-Base

Table C.1. Numerical Data (Temperature)

welding_type	temperature_max	temperature_min
GTAW	3000.00	100.00
GMAW	3000.00	100.00
PAW	3000.00	100.00
LBW	3000.00	100.00
EBW	3000.00	100.00
RW	3000.00	100.00
FW	3000.00	100.00
SW	3000.00	100.00
TW	3000.00	100.00
GTAB	3000.00	100.00
GMAB	3000.00	100.00
EBB	3000.00	100.00
LBB	3000.00	100.00
	(K)	(K)

Table C.2. Numerical Data (Equipment Weight)

welding_type	equipment_weight_min
GTAW	50.00
GMAW	100.00
PAW	100.00
LBW	100.00
EBW	100.00
RW	150.00
FW	10.00
SW	10.00
TW	1.00
GTAB	50.00
GMAB	100.00
EBB	100.00
LBB	100.00
	(KG)

Table C.3. Numerical Data (Power Capacity)

welding_type	power_capacity_max	power_capacity_min
GTAW	100.00	2.00
GMAW	100.00	3.00
PAW	100.00	3.00
LBW	100.00	2.00
EBW	100.00	2.00
RW	100.00	5.00
FW	1.00	0.10
SW	100.00	2.00
TW	0.10	0.01
GTAB	100.00	2.00
GMAB	100.00	3.00
EBB	100.00	2.00
LBB	100.00	2.00
	(KW)	(KW)

Table C.4. Numerical Data (Microgravity)

welding_type	micro_gravity_max	micro_gravity_min
GTAW	1.00	0.00
GMAW	1.00	0.00
PAW	1.00	0.00
LBW	1.00	0.00
EBW	1.00	0.00
RW	1.00	0.00
FW	1.00	0.00
SW	1.00	0.00
TW	1.00	0.00
GTAB	1.00	0.00
GMAB	1.00	0.00
EBB	1.00	0.00
LBB	1.00	0.00
	(G)	(G)

Table C.5. Numerical Data (Pressure)

welding_type	pressure_max	pressure_min
GTAW	1.00E+00	2.50E-02
GMAW	1.00E+00	2.50E-02
PAW	1.00E+00	0.00E+00
LBW	1.00E+00	0.00E+00
EBW	2.00E-02	0.00E+00
RW	1.00E+00	0.00E+00
FW	1.00E+00	0.00E+00
SW	1.00E+00	0.00E+00
TW	1.00E+00	0.00E+00
GTAB	1.00E+00	2.50E-02
GMAB	1.00E+00	2.50E-02
EBB	2.00E-02	0.00E+00
LBB	1.00E+00	0.00E+00
	(atm)	(atm)