

THE SCRAM TOOL-KIT

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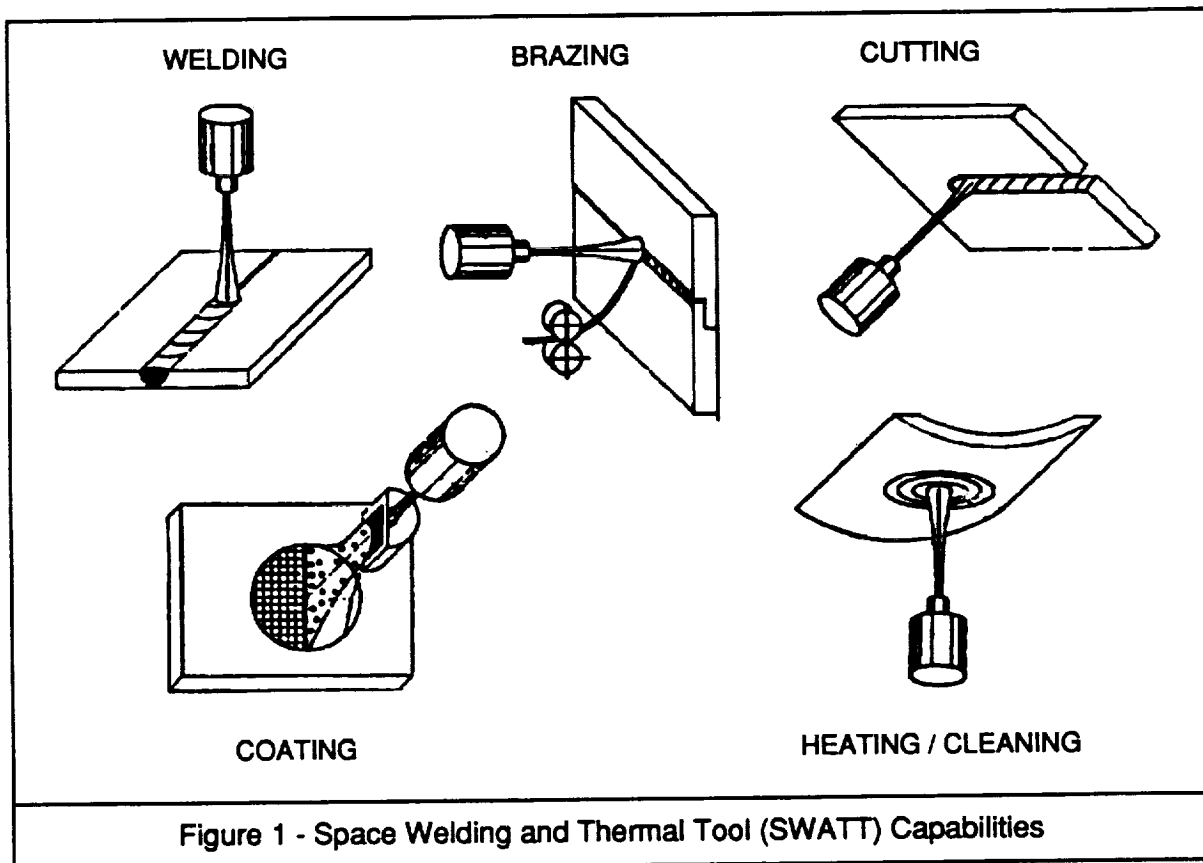
ABSTRACT

This paper proposes a new series of on-orbit capabilities to support the near-term Hubble Space Telescope, Extended Duration Orbiter, Long Duration Orbiter, Space Station Freedom, other orbital platforms, and even the future manned Lunar / Mars missions. These proposed capabilities form a tool-kit termed Space Construction, Repair, and Maintenance (SCRAM). SCRAM addresses both Intra-Vehicular Activity (IVA) and Extra-Vehicular Activity (EVA) needs. SCRAM provides a variety of tools which enable welding, brazing, cutting, coating, heating, and cleaning, as well as corresponding non-destructive examination. Near-term IVA-SCRAM applications include repair and modification to fluid lines, structure, and laboratory equipment inside a shirt-sleeve environment (i.e. inside Spacelab or Space Station). Near-term EVA-SCRAM applications include construction of fluid lines and structural members, repair of punctures by orbital debris, refurbishment of surfaces eroded by atomic oxygen, and cleaning of optical, solar panel, and high emissivity radiator surfaces degraded by contaminants. The SCRAM tool-kit also promises future EVA applications involving mass production tasks automated by robotics and artificial intelligence, for construction of large truss, aerobrake, and nuclear reactor shadow shield structures. The leading candidate tool processes for SCRAM, currently undergoing research and development, include Electron Beam, Gas Tungsten Arc, Plasma Arc, and Laser Beam. A series of strategic space flight experiments would make SCRAM available to help conquer the space frontier.

INTRODUCTION

Today, we do not have enough on-orbit construction, repair, and maintenance capabilities to effectively support aggressive space programs: such as Hubble Space Telescope (HST), Extended Duration Orbiter (EDO), Long Duration Orbiter (LDO), Space Station Freedom (SSF), other orbital platforms, and manned Lunar / Mars missions. Therefore, it's critical that we expand our on-orbit capabilities and develop new tools to deal with the more demanding tasks that lie closely ahead. The Space Construction Repair and Maintenance (SCRAM) tool-kit will provide us with some of the tools needed to prevail through our space programs, and eventually help us conquer the space frontier. SCRAM provides tools for both our intra-vehicular activity (IVA) and extra-vehicular activity (EVA) needs.

Since the 1960's, extensive research and development (R&D) efforts have occurred, trying to achieve on-orbit welding capability. Consequently, several thermal processes have been investigated and are still being refined today. These include electron beam, gas tungsten arc, plasma arc, and laser beam. In addition to welding, however, other capabilities have been shown feasible with these same thermal processes. Accordingly, this paper establishes the term Space Welding and Thermal Tools (SWATT) to collectively identify several multi-function processes (tools) which are capable of welding, brazing, cutting, coating, heating, and even cleaning (see Figure 1). The SCRAM tool-kit has been devised to house SWATT and its complementary quality assurance and control tools, which would perform on-orbit in-situ non-destructive examination (NDE) of the workpiece. SCRAM would also house workpiece surface preparation tools and set-up assemblies. ***



NEED FOR SCRAM

The need for SCRAM is manifested by the limitations of our current on-orbit capabilities. In-space joining, NDE, cutting, coating, heating, and cleaning are all tasks which cannot be effectively (if at all) accomplished with NASA's existing tools. SCRAM offers multi-function tools which will offer all of these new capabilities. Consequently, challenging space endeavors (see Figure 2) will become feasible.

*** Note: Detailed discussion of EVA-SCRAM application scenarios and performance and safety issues is presented in a separate paper at this Symposium, titled "EVA-SCRAM Operations."

Need for Better In-Space Joining: The in-space joining techniques, currently available to NASA, are limited to mechanical fastening and adhesive bonding. These techniques are rendered inadequate when compared to the following higher-performance joining characteristics of SCRAM's SWATT:

- Higher Joint Strength and Rigidity
- Better Joint Hermeticity
- Lower Joint Mass
- Simpler Joint Design
- Simpler Joint Manufacturing
- Higher Joint Reliability
- Broader Repair Versatility
- Lower Cost

Need for In-Space NDE: NDE of joints on-orbit is currently limited to simple visual inspection. In-space NDE is necessary to determine integrity and life-span of reusable on-orbit platforms. In addition, in-situ NDE is a necessary complement to SWATT operations (i.e. welding). NDE would provide in-space quality assurance and control of welded joints. SCRAM's NDE tools would provide accurate assessment of a joint's structural integrity (i.e. detection of cracks, voids, lack of penetration, misalignment) via electrical, ultrasonic, x-ray, and optical means, which far exceed the information gathered with a simple visual inspection. In addition, other SCRAM optical-NDE means would be used to monitor surface contamination / coating during or after a cleaning operation or a welding / cutting / coating operation.

Need for Better In-Space Cutting: In-space cutting is a task reserved only for emergency repair; routine construction would employ pre-cut and machined material. The in-space cutting techniques currently available to NASA are limited to sawing and chip-less blade cutting. These techniques have limited applications. Sawing operations generate debris which is difficult to contain in the micro-gravity / vacuum environment. Chip-less blade cutting is limited to few materials and workpiece geometries. SCRAM's SWATT "cutting torch" capability, would offer a repair tool which is more flexible with materials and workpiece geometries.

Need for In-Space Coating: Today, NASA cannot refurbish in space surfaces which have been eroded by atomic oxygen bombardment. SSF and any other platforms, which will remain in Low Earth Orbit (LEO) for long periods of time, will sustain significant damage to critical spacecraft surfaces, seriously degrading mission performance. Some of the surfaces being addressed are used as thermal radiators, telescope mirrors, electric conductors, and transmission or receiving antennae. Total replacement of such surfaces is currently the only alternative. However, the capability to re-coat such eroded surfaces would be achievable with SCRAM's SWATT.

Need for In-Space Heating: Currently NASA cannot locally heat and free a stuck antenna deployment joint (cold-welded in-place), or heat-treat structural elements which have lost material temper due to prolonged exposure to radiation and thermal gradients in space. SCRAM's SWATT would provide a localized heat-treating capability. This capability would also aid SWATT cutting, by introducing a



Figure 2 - Need for Space Construction, Repair, and Maintenance (SCRAM) Tools

thermal gradient across the cut plane prior to the cutting operation; this will yield a smoother cut edge [ref-1]. Moreover, SWATT's heating source could be used as a research tool for high temperature rapid-melt and re-solidification experiments (for both IVA and EVA experiments).

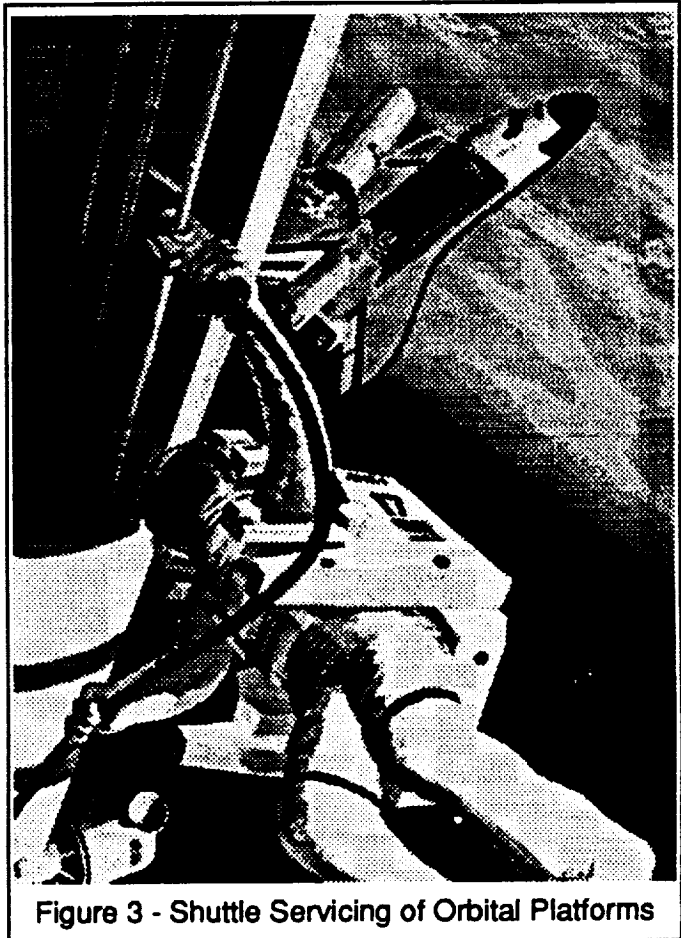
Need for In-Space Cleaning: Today, NASA cannot clean optical, solar collector, or thermal control surfaces which are permanently exposed to the extra-vehicular space environment. Performance of windows, mirrors, lenses, high emissivity radiator surfaces, and solar panel surfaces are gradually degraded by polymerized and cross-polymerized organic contamination (hydrocarbons and siloxanes), generated primarily by exposure with the vacuum and ultraviolet radiation environment [ref-4]. These contaminants, in-part, are generated by spacecraft outgassing products, fuel, and propulsion by-products. SCRAM's SWATT would provide means for cleaning such contaminants.

SCRAM APPLICATIONS

SCRAM's SWATT and NDE capabilities of welding, brazing, cutting, coating, heating, cleaning, and inspection lend themselves to various applications in near-term Shuttle and SSF missions, and in future manned Lunar / Mars missions.

Shuttle Missions: On-going Shuttle missions carry two tool-kits for in-flight contingencies. The IVA kit is called In-Flight Maintenance (IFM) tools, and is stowed in a middeck locker. The EVA kit is called Provisions Stowage Assembly (PSA) tools, and is stowed in the cargo bay. IVA- and EVA-SCRAM tools will complement and improve the IFM's and PSA's existing repair capabilities during contingencies. Longer duration Shuttle missions (EDO / LDO), with on-orbit stays reaching 30 to 90 days, will need to be capable of repairing punctures by orbital debris or damage by fatigue to the crew compartment, Spacelab module, tunnel adapter, external airlock, radiator panels, or vehicle structure (i.e. cargo-bay doors and latching mechanisms). In addition, shuttle servicing missions of LEO platforms and satellites could employ SCRAM for repair and maintenance of these spacecraft (i.e. cleaning of HST optics). SCRAM tools could be employed with Shuttle missions via manual or semi-automated operation modes (see Figure 3). Teleoperated SCRAM applications may also be feasible, should the Shuttle arm, the remote manipulating system (RMS), be improved for more dexterous operations (i.e. with the Dexterous End Effector now under development). In addition, teleoperation or even autonomous robotic operation of SCRAM may be achievable using a dedicated robotic slave arm (i.e. with the Servicing Aid Tool, also under development).

SSF Missions: SSF will present multiple opportunities for repair, maintenance, and construction over its life-span. SCRAM tools would become critical for repair of orbital debris- or fatigue-damaged habitation / laboratory modules, radiators, pressurized fluid systems, and structure (see Figure 4). Maintenance of surfaces eroded by atomic oxygen or degraded by contamination, and construction of modifications or expansions to the station structure, habitation / laboratory modules, and power and thermal systems, will become a routine well suited for SCRAM. Even general metallic labo-



ratory equipment aboard SSF (i.e. containers, fluid lines, brackets) will require repair, maintenance, and modification; welding is commonly used for such purposes terrestrially.

Lunar Outpost Missions: The imminent renewal of manned Lunar missions will open a myriad of opportunities for SCRAM to be heavily employed both IVA and EVA in construction, repair, and maintenance of structures, habitation/laboratory modules, antennae, solar collector arrays, power plants, fluid lines (plumbing), surface vehicles, descent-ascent vehicles, and other various equipment (see Figure 5).

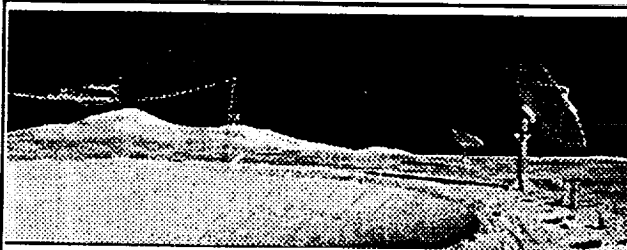


Figure 5 - Lunar-Based Antennae Construction

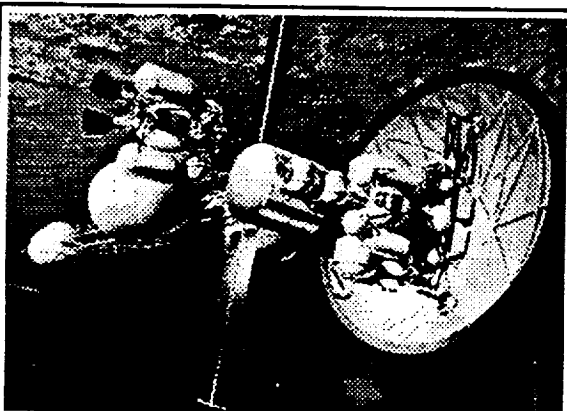


Figure 6 - Mars Orbital Transfer Vehicle's Aerobrake Construction

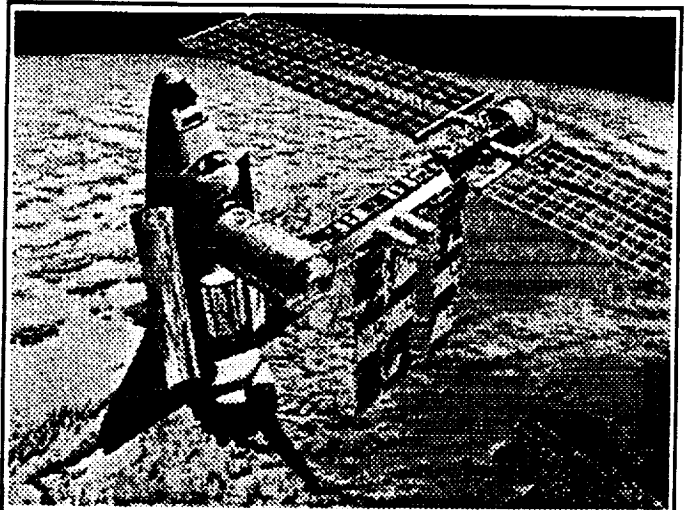


Figure 4 - SSF Construction, Repair, and Maintenance

Manned Mission to Mars: The eventual manned missions to Mars will consist of LEO preparation, interplanetary transfer, low Mars orbit, landing and exploration, and return-to-Earth phases. Over all these phases, manned Mars missions may employ

SCRAM tools, both IVA and EVA, on the orbital transfer, descent, ascent, and surface vehicles. The vehicles' construction, repair, and maintenance tasks suited for SCRAM will involve structures, habitation/laboratory modules, aerobrakes, antennae, solar collector arrays, radiators, power plants, nuclear shadow shields, fluid lines, and other various equipment (see Figure 6).

SCRAM PROCESSES

The SCRAM tool-kit is based on SWATT and complementary NDE tools. SWATT employs a combination of electron beam (EB), gas tungsten arc (GTA), plasma arc (PA), and laser beam (LB) processes to accomplish welding, brazing, cutting, coating, heating, and clean-

ing tasks. Complementary in-situ NDE tools employ electrical, ultrasonic, x-ray, and optical processes to accomplish in-space quality assurance and control. Even though some of these SWATT and NDE processes overlap in their capabilities, each process exhibits unique and essential characteristics. Therefore, all of the processes are essential to effectively support anticipated SCRAM applications.

EB-SWATT: The EB process accelerates and directs a dense stream of high-velocity electrons upon an electrically conductive surface, to which the kinetic energy of the electrons is transferred as heat. Changing the beam focus varies the EB's intensity and consequently its capabilities (i.e. welding vs. cleaning). EB is limited to EVA (vacuum) operation only.

GTA-SWATT: The GTA process employs an ionization medium, provided by an inert gas, to transfer an arc from a non-consumable tungsten electrode to an electrically conductive surface. The high electric current, flowing through the arc and into the workpiece, generates heat. Changing GTA's current and ionization-gas flow-rate parameters allows various IVA and EVA capabilities (i.e. welding vs. coating). Vacuum operation is enabled using a Rockwell patented hollow tungsten electrode, through which an ionization medium (argon) is provided.

PA-SWATT: The PA process accelerates and converges a hot plasma, heated within the PA device by an arc, upon any surface whether electrically conductive or not. Changing PA's current and plasma-gas flow-rate parameters allows various IVA and EVA capabilities (i.e. welding vs. cutting). Vacuum operation is enabled using arc-jet space propulsion technology.

LB-SWATT: The LB process employs a high-power coherent monochromatic light beam for heating any material at the beam's point of focus. The LB is generated by either an Nd-YAG crystal or a CO₂ gas, and may be directed and focused upon the workpiece by a system of mirrors, lenses, and fiber-optics. Changing LB's power and focus allows various IVA and EVA capabilities (i.e. welding, cutting).

Electrical-NDE: SWATT fabrication (i.e. weld) quality information is largely contained in the process' electrical feedback signals. These signals can be sampled by a voltage tap and a Hall-effect current transducer. This consequent electrical feedback can be compared after the SWATT operation to predetermined acceptable limits, or the feedback can be processed real-time by a computer allowing adaptive control of SWATT's operation parameters. SCRAM's electrical NDE methods, for post-fabrication detection of flaws, also includes eddy-current techniques.

Ultrasonic-NDE: SCRAM's ultrasonic-NDE processes employ both contacting and non-contacting methods for generating ultrasonic waves, including piezoelectric transducers with built-in dry couplants, and electro-magnetic-acoustic transducers (EMAT).

X-Ray-NDE: SCRAM's X-ray radiography is one of its most powerful and reliable methods for NDE due to its direct flaw visualization capability.

Optical-NDE: SCRAM's optical-NDE processes for surface flaw detection include holography, shearography, and speckle interferometry. These methods are based on the interaction between the object and a laser beam, providing optical fringe patterns. Dynamic thermal gradients, caused in LEO every 45 minutes by passage through the terminator, may provide sufficient stress on the workpiece to support SCRAM's optical-NDE processes. In addition to flaw detection, SCRAM employs optically stimulated electron emission (OSEE) and laser fluorescence techniques for characterizing surface contamination or coating by metal vapor deposition.

DEVELOPING SCRAM

R&D efforts to achieve SCRAM capabilities, need to target combined interactions between the following varying factors: (1) SCRAM processes (i.e. SWATT, NDE), (2) intra- and extra- vehicular operational environments (i.e. microgravity, vacuum, atmosphere, background radiation, thermal gradients), and (3) workpiece materials and geometries (i.e. stainless steels, aluminums, titaniums, Inconels, composites). In addition, R&D efforts need to focus on the various SCRAM operation modes (manual, telerobotic, semi-automated, fully-automated) and their implications on crew and mission safety. These R&D efforts should maximize utility of ground based space simulation tools, such as KC-135 parabolic flights, vacuum chambers, neutral buoyancy water tanks, and numerical modelling. R&D efforts should obviously continue and proceed to space-based validation and demonstration using Shuttle Small Payload experiments (i.e. Get Away Special, Complex Autonomous Payload, Hitchhiker), Spacelab IVA experiments (i.e. glove-box), and Shuttle EVA experiments (i.e. cargo-bay mounted workstation). Some of this R&D has been completed, but much still remains to be done.

R&D efforts pursuing development of SWATT and NDE have mainly occurred, and continue, in the former Soviet Union (Russia and Ukraine) and in the US. However, the Japanese and Europeans have also entered this field of endeavor. Today, EB-SWATT development is being led by the Paton Institute of Ukraine, the GTA-SWATT by Rockwell International Corporation of the US and NPO Tekhnomash of Russia, the PA-SWATT by NASA Marshall Space Flight Center (MSFC), and the LB-SWATT by University of Tennessee-Calspan (CO₂ laser) and University of Alabama (Nd-YAG laser). Development of SCRAM NDE tools is being led by NASA Langley Research Center (LaRC).

EB-SWATT Status: The former Soviet Union, via the Paton Institute in Ukraine, successfully accomplished the following R&D for in-space EB: ground based vacuum chamber tests, microgravity simulation aircraft flight tests, on-orbit spacecraft autonomous flight experiments (with Soyuz-6), on-orbit space station autonomous experiments (with Salyut-6, -7, and MIR), ground-based neutral buoyancy water tank EVA simulation tests, and finally on-orbit manual EVA experiments (off of Salyut-7, and MIR, see Figure 7) [ref-1]. These aggressive efforts have resulted in Paton's in-space EB tool, which is known as "URI" or the "Versatile Hand Tool (VHT)." Today, the VHT is incorporated into MIR's on-board tool base. In-fact, the VHT has already been applied in real operations, including truss construction (by welding joints), emergency repair of a broken antennae (by cutting it loose), and refurbishment of solar panel performance (by cleaning debris off panel surfaces) [ref-2]. The VHT's performance with US alloys, and safety characteristics under NASA on-orbit operation standards are yet to be determined. Currently, NASA Goddard Space Flight Center (GSFC) is pursuing funding for an extensive series of Shuttle experiments to safely and effectively characterize in-space EB methods with Paton devices. NASA GSFC plans to incorporate a yet to be announced consortium of US experts, composed of NASA centers, other government agencies, industry, and universities.

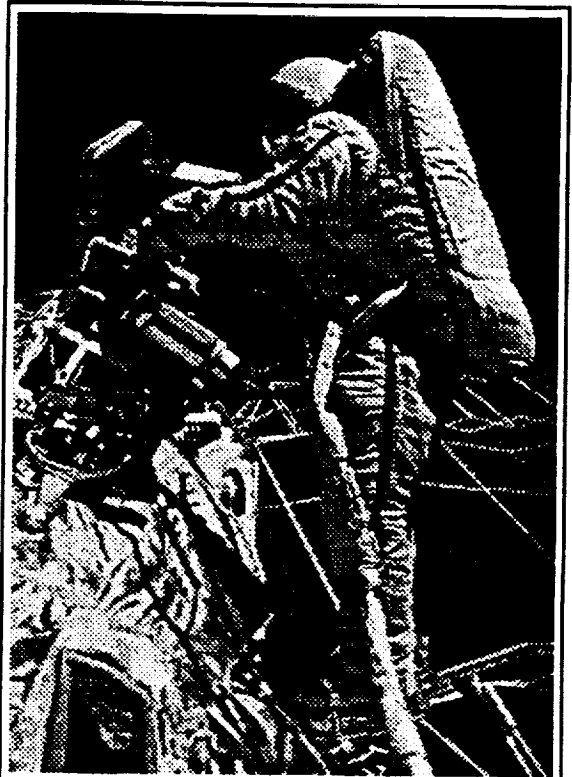


Figure 7 - Former Soviet Union EVA Manual Welding Experiment

GTA-SWATT Status: Rockwell International Corporation of the US successfully accomplished the following via Independent R&D, and some direct contracts from NASA MSFC and a NASA Headquarters In-STEP program: development of hollow electrode patents for GTA in a vacuum (4,803,339 & 5,149,932), ground based vacuum chamber tests, microgravity simulation KC-135 flight tests of semi-automated and manual welding tasks, development of an autonomous Get Away Special (G-169) Shuttle payload for on-orbit testing (see Figure 8), KC-135 flights of G-169, design of a more capable Shuttle Welding Experiment Platform (SWEP), ground-based neutral buoyancy water tank EVA simulation tests of semi-automated welding tasks, and designs of on-orbit Shuttle IVA and EVA experiments [ref-3]. Currently, NASA GSFC is pursuing funding for an extensive consortium-developed series of Shuttle experiments to safely and effectively characterize in-space GTA methods. Outside of the US, NPO Tekhnomash of Russia has successfully accomplished efforts very similar to Rockwell's. In August 1992, Tekhnomash presented photographs of their in-space EVA-GTA torch prototypes, including manual and semi-automated orbital versions. Tekhnomash is preparing to test these in space. In summary, all ground-based evaluations of the in-space GTA promise success and effective applications on-orbit.

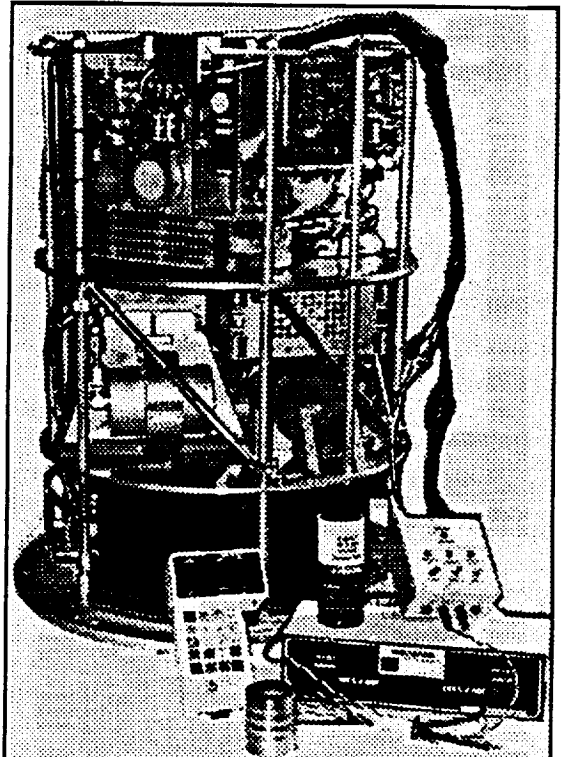


Figure 8 - Rockwell's Get Away Special GTA Welding Experiment

PA-SWATT Status: NASA MSFC and a California based sub-contractor, which specializes in arc-jet propulsion technology, are currently developing a PA device for vacuum operation. The potential for this technology's successful development is high. But, few details are known at this time, due to the infancy of the technology and its consequent proprietary nature.

LB-SWATT Status: The University of Tennessee-Calspan is currently pursuing development of a Shuttle-Small-Payload-type (cargo-bay) LB experiment with a CO2 laser. This experiment is manifested for flight around 1995, and is being funded through a NASA Headquarters' Center for the Commercial Development of Space. On the other hand, University of Alabama in Huntsville conducted microgravity-simulation-aircraft flight experiments on NASA MSFC's KC-135. These experiments targeted LB with Nd-YAG laser. The University of Alabama is currently pursuing funding to continue this work. Even though lasers seem to be the "thing of the future," LB's near-term utility in space suffers from very high power requirements.

NDE Status: Development of NDE processes has been primarily focused on terrestrial applications. However, these developed NDE technologies, for the most part, are almost directly applicable to on-orbit operations. Extensive R&D remains to be done in the conversion of these terrestrial NDE technologies into on-orbit compatible tools [ref-5].

DESCRIPTION OF THE SCRAM TOOL-KIT

Since the Space Shuttle is the only near-future space construction, repair, and maintenance shop, SCRAM is designed for Shuttle use. The SCRAM tool-kit supports both IVA and EVA operations. Consequently, SCRAM is separated into two distinct tool-sets.

The IVA-SCRAM Set: The IVA-SCRAM set of tools would be stowed in the Shuttle's Middeck Lockers (see Figure 9). It is anticipated that two lockers would be required, one for IVA-SCRAM's computer-controlled power supply unit, and the other for IVA-SCRAM's SWATT, NDE, consumables, and other support devices. IVA-SCRAM's computer-controlled power supply (hardware and software) would be a derivative of the Centaur III

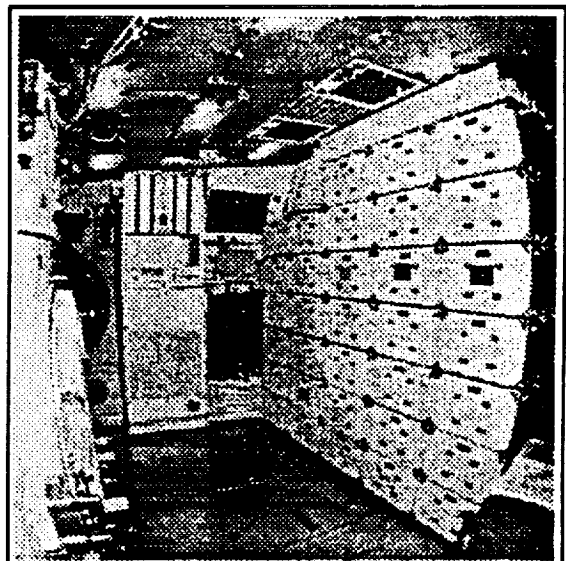


Figure 9 - IVA SCRAM Stowage

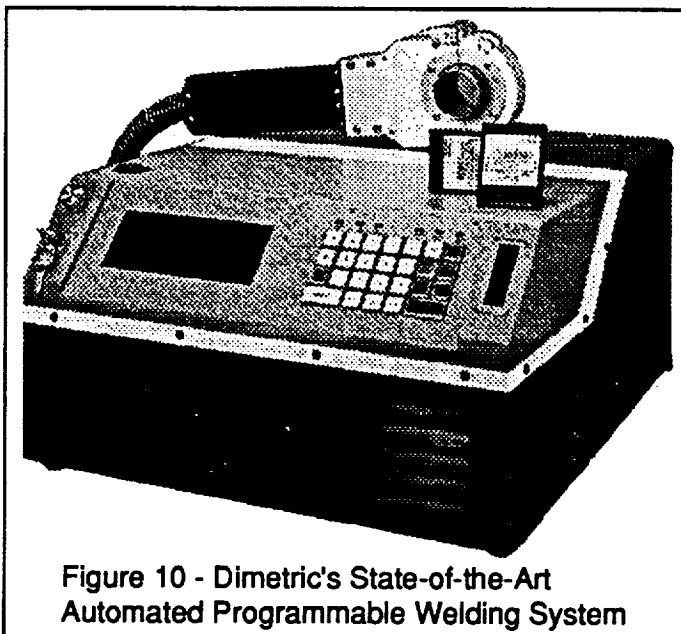


Figure 10 - Dimetric's State-of-the-Art Automated Programmable Welding System

150PTW, developed by Dimetrics of Talley Industries (see Figure 10). The Centaur III is commercially proven in terrestrial food, dairy, beverage, pharmaceutical, biomedical, semiconductor, nuclear, aircraft, and aerospace industries. It provides user-friendly programmable interfaces with the operator, and employs read / write memory cassette cartridges which allow use or modification of pre-programmed procedures (i.e. for welding). IVA-SCRAM's power supply would process Orbiter power and distribute it under computer control to the SWATT and NDE devices. SWATT devices suitable for IVA would include a manual GTA welding torch and a semi-automated GTA orbital welding head (see Figure 10). The GTA devices would be supplemented with electrical and ultrasonic NDE. In addition, the IVA-SCRAM

set would include safety devices for protection against temperature extremes, electrical shock, contamination (i.e. argon shielding gas), and radiation (i.e. EMI, ultraviolet, infrared, intense light). Portable workstation set-up and workpiece surface preparation tools would also be included.

The EVA-SCRAM Set: The EVA-SCRAM set of tools would be stowed in the Shuttle's cargo bay. But, due to the more demanding extra-vehicular environment, extensive flight hardware and software would be required to facilitate EVA-SCRAM operations. Therefore, EVA-SCRAM would be designed to maximize use of existing and upcoming Shuttle EVA facilitating tools, including the telerobotic RMS, Dextrous End Effector (DEE), and Servicing Aid Tool (SAT). A Cargo Bay Stowage Assembly (CBSA) type tool carrier (see Figure 11) mounted to the cargo bay's sidewall could be employed for stowing workstation set-up assemblies, workpiece surface preparation tools, SWATT, and NDE tools. The CBSA

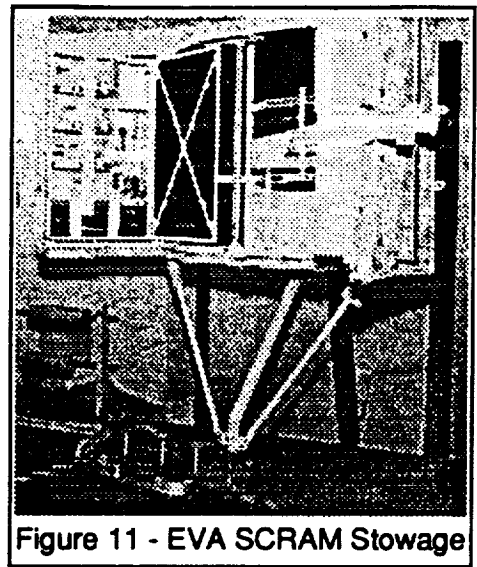


Figure 11 - EVA SCRAM Stowage

type "locker" provides EVA crewmember with proper foot and hand restraints so that tool boards can be transferred onto the Extravehicular Mobility Unit (space suit) and supporting tool caddies, such as the Manipulator Foot Restraint (MFR) (see Figure 12). The Flight Servicing System (FSS) locker may also be used for both tool stowage and transportation to the worksite using the RMS. The CBSA or FSS would contain a specialized harness for interfacing the modular EVA-SCRAM tools with power, control, coolant, and consumables (i.e. ionization gas). The harness could be routed along the RMS (i.e. using velcro straps) and be connected to a Get Away Special (GAS) Canister, which would contain SCRAM's computer controlled power supply unit, radiator, and consumables. The GAS canister would provide a one atmosphere dry nitrogen environment, allowing the use of non-vacuum hardened support equipment (similar to IVA-SCRAM's - see Figure 10). The GAS canister would also provide standard interfaces to Orbiter power and aft flight deck control. In the near-term, SWATT devices suitable for EVA would include EB, GTA, PA, and LB. These SWATT devices would be supplemented with electrical, ultrasonic, optical, and x-ray NDE tools. In addition, the EVA-SCRAM set would include safety devices for protection against temperature extremes, electrical shock, contamination (i.e. metal vapor), and radiation (i.e. EMI, x-ray, UV, infrared, intense light).

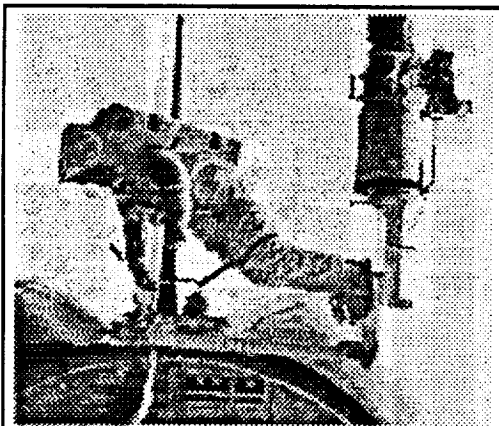


Figure 12 - RMS-MFR Supporting EVA SCRAM

CONCLUSION

Today, we have the technologies necessary for developing a SCRAM tool-kit. However, validation and demonstration of SWATT and NDE technologies in space, by the US, have yet to occur. With increasing Shuttle mission challenges and upcoming endeavors such as SSF, SCRAM tools can provide critical construction, repair, and maintenance capabilities needed in the harsh frontier of space. Flight experiments are necessary to complete the development of SCRAM tools, and their incorporation into the nation's Space Exploration Initiative. Experiments, targeting all SWATT and NDE processes, should be cost-effectively carried out with the same flight platform, such that the various processes' capabilities can be comparatively characterized and evaluated against near-term applications. Shuttle Small Payloads are effective for carrying out safely an autonomous series of such experiments. Consecutively, more demanding Spacelab glove-box IVA experiments and Shuttle cargo bay EVA experiments can be undertaken to validate and demonstrate manual, telerobotic, semi-automated, and fully-automated SCRAM operation modes for near-term applications.

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