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EVA-SCRAM OPERATIONS

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by

David Tamir
Rockwell International Corporation
Space Systems Division
Mail Code ZK32
Kennedy Space Center, FL 32815
Tel. (407) 861-4744

Lee A. Flanigan
Rockwell International Corporation
Rocketdyne Division
950 Explorer Blvd., Suite 3B
Huntsville, AL 35806
Tel. (205) 544-2643

Jack L. Weeks
Rockwell International Corporation
Rocketdyne Division
950 Explorer Blvd., Suite 3B
Huntsville, AL 35806
Tel. (205) 544-2741

Sidney R. McClure
NASA Goddard Space Flight Center
Aerospace Welding Laboratory
Mail Code 752.1
Greenbelt, MD 20771
Tel. (301) 286-2103

Andrew G. Kimbrough
Dimetrics Incorporated
Talley Industries
404 Armour St.
Davidson, NC 28036
Tel. (704) 892-8872

ABSTRACT

This paper wrestles with the on-orbit operational challenges introduced by the proposed Space Construction, Repair, and Maintenance (SCRAM) tool kit for Extra-Vehicular Activity (EVA). SCRAM undertakes a new challenging series of on-orbit tasks in support of 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 new EVA tasks involve welding, brazing, cutting, coating, heat-treating, and cleaning operations. Anticipated 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 which have been degraded by contaminants. Future EVA-SCRAM applications are also examined, involving mass production tasks automated with robotics and artificial intelligence, for construction of large truss, aerobrake, and reactor shadow shield structures. Realistically achieving EVA-SCRAM is examined by addressing manual, teleoperated, semi-automated, and fully-automated operation modes. The operational challenges posed by EVA-SCRAM tasks are reviewed with respect to capabilities of existing and upcoming EVA systems, such as the Extra-vehicular Mobility Unit, the Shuttle Remote Manipulating System, the Dexterous End Effector, and the Servicing Aid Tool.

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 (see Figure 1). Employing extra-vehicular activity (EVA) SCRAM tools presents new challenges with on-orbit operations. This paper will focus on EVA-SCRAM's applications and the corresponding on-orbit and even Lunar surface scenarios and performance and safety issues. ***

Figure 5 - Need for Space Construction, Repair, and Maintenance (SCRAM) Tools

EVA-SCRAM DEFINITIONS

This paper will employ the following definitions, some of which are specifically tailored for this paper's discussion. **EVA-SCRAM** encompasses construction, repair, and maintenance which occur outside the pressurized hull of the spacecraft (in-vacuum), whether it's on-orbit or on the Lunar surface. **On-orbit** includes low Earth orbit (LEO), Lunar transfer, Lunar, Mars transfer, and Mars orbits. **In-Space** includes both on-orbit and Lunar-surface operations. **EVA-SCRAM operations** do not have to involve EVA crewmembers, they may be executed by telerobotics alone. **Telerobotics** means that telepresence is being used to operate a robotic slave arm. **Telepresence** (teleoperation) means that sensor feedback (i.e. visual) from the EVA-SCRAM worksite is relayed real-time to a crewmember inside the spacecraft, so he may remotely assist or execute an EVA-SCRAM operation. A **robotic** slave arm may be teleoperated or fully-automated. **Full-automation** means that artificial intelligence is being employed by a machine to execute a set of continuous tasks, requiring no human intervention. **Artificial Intelligence** means that the fully-automated device employs sensors to gather real time feedback on the operation, and accordingly be capable of adapting the operation parameters to dynamic factors. **Semi-automation** means that a task is accomplished by a pre-programmed device, which has been manually or telerobotically set-up and activated. **Manual** means that the EVA crewmember has to use his own body (i.e. hands, senses) to accomplish a task. **Operation modes** include: (1) manual, (2) teleoperation, (3) semi-automation, (4) full-automation. In summary, the following are potential **EVA-SCRAM operation modes**: (1), (1+2), (1+3), (1+2+3), (2), (2+3), or (4).

EVA-SCRAM CAPABILITIES

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

*** Note: Detailed discussion of the need, processes, development, and description of the SCRAM tool-kit is presented in a separate paper at this Symposium, titled "The SCRAM Tool-Kit."

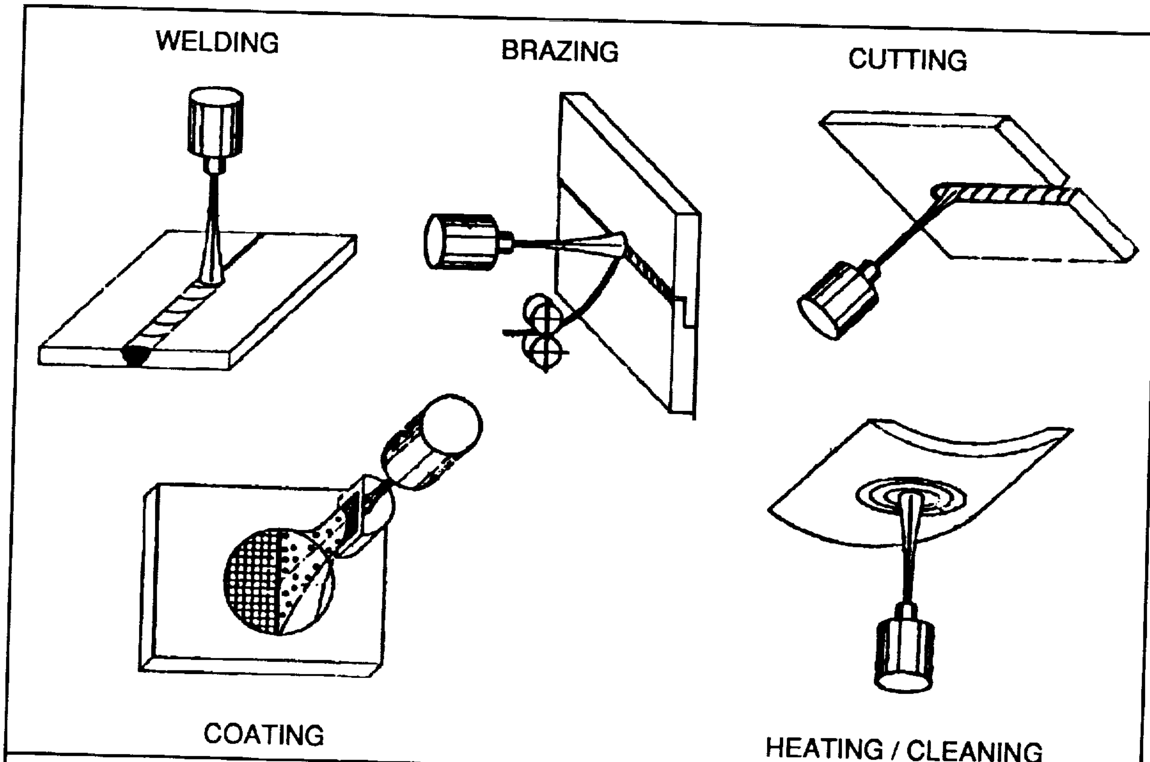

Figure 2 - Space Welding and Thermal Tool (SWATT) Capabilities

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 thermal processes. Accordingly, this paper employs 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 2). 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's NDE tools employ electrical, ultrasonic, x-ray and optical processes (i.e. eddy current, EMAT, radiography, laser refraction). SCRAM would also house work-piece surface preparation tools and set-up assemblies.

EVA-SCRAM APPLICATIONS

EVA-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. The EVA-SCRAM applications set various new challenges for manual, teleoperated, semi-automated, and fully-automated EVA operation modes, both on-orbit and on the Lunar surface.

Shuttle Missions: On-going Shuttle missions carry an EVA tool-kit for in-flight contingencies. This kit is called Provisions Stowage Assembly (PSA) tools, and is stowed in the cargo bay. EVA-SCRAM tools will complement and improve the 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 EVA-SCRAM for repair and maintenance of these spacecraft (i.e. cleaning of HST optics). EVA-SCRAM tools could be employed with Shuttle missions via a combination of manual, semi-automated, and telepresence techniques (see Figure 3). Direct teleoperation of EVA-SCRAM tools may also be feasible, should the Shuttle arm, the remote manipulating system (RMS), be improved for more dexterous operations (i.e. with the Dextrous End Effector now under development). In addition, teleoperation or even full automation of EVA-SCRAM may be achievable using a dedicated robotic slave arm (i.e. the Servicing Aid Tool, also under development).

SSF Missions: SSF will present multiple opportunities for repair, maintenance, and construction over its life-span. EVA-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 EVA-SCRAM.

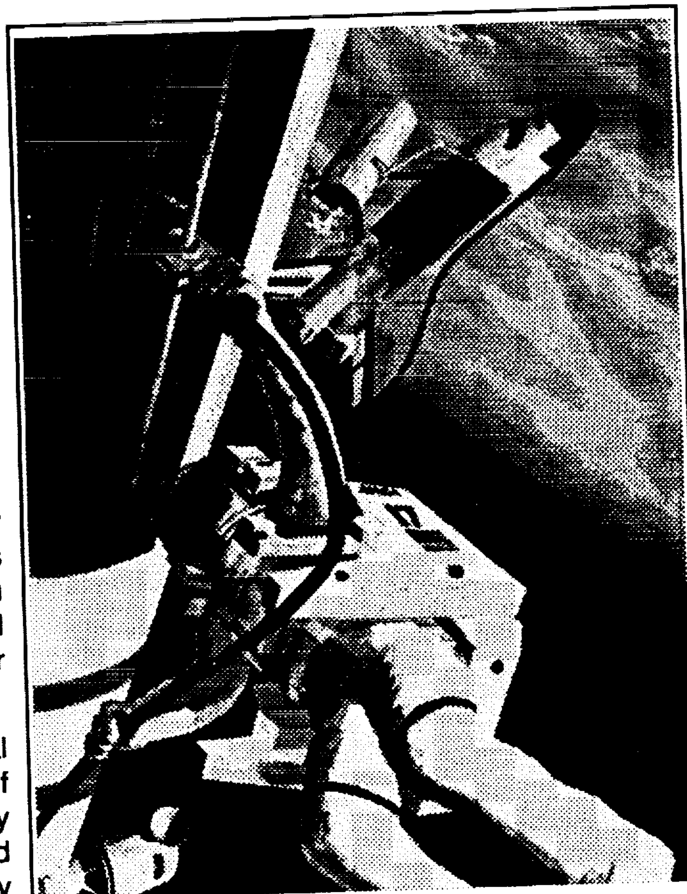

Figure 3 - Shuttle Servicing of Orbital Platforms

Lunar Outpost Missions: The imminent renewal of manned Lunar missions will open a myriad of opportunities for EVA-SCRAM to be heavily employed 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 5-6).

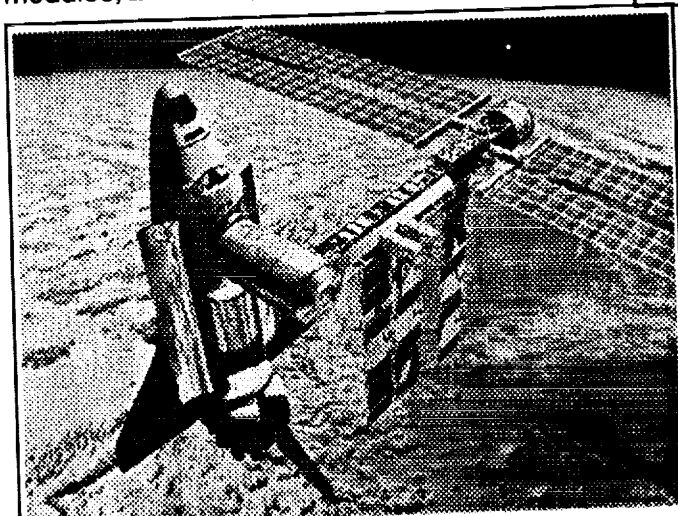

Figure 4 - SSF Construction, Repair, and Maintenance

Figure 5 - Lunar Outpost Construction

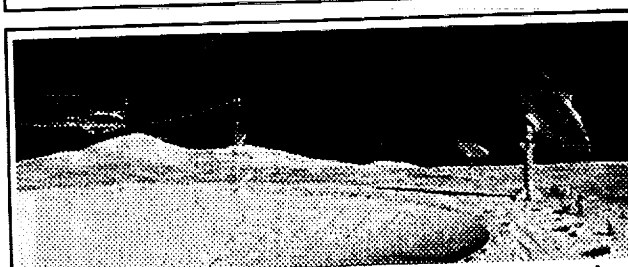

Figure 6 - Lunar-Based Antennae Construction

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 could employ EVA-SCRAM tools on the orbital transfer, descent, ascent, and surface vehicles. The vehicles' construction, repair, and maintenance tasks suited for EVA-SCRAM will involve structures, habitation / laboratory modules, aerobrakes, antennae, solar collector arrays, radiators, power plants, nuclear shadow shields, fluid lines, and various other equipment (see Figures 7-8).

Figure 7 - Mars Orbital Transfer Vehicle's Aerobrake Construction

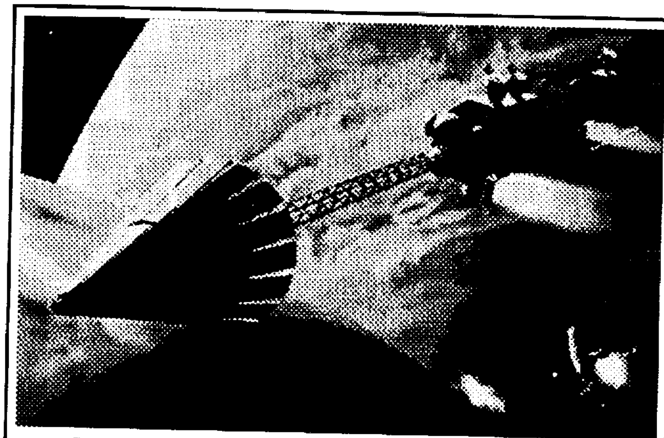

Figure 8 - Vehicle's Nuclear Reactor Shadow Shield Construction

EVA-SCRAM SCENARIOS

Nearest-term EVA-SCRAM operations will include construction of fluid lines, construction of structural members, repair of orbital-debris punctures, refurbishment of surfaces eroded by atomic oxygen, and cleaning of contaminated optics solar panels, and high emissivity radiator surfaces. Additional future EVA-SCRAM operations will include mass production tasks, such as construction of large orbital trusses, aerobrakes, nuclear reactor shadow shields, and Lunar outpost structures. These projected tasks (near-term and future) introduce unique scenarios for both on-orbit and Lunar surface EVA operations. It is anticipated that the near-term EVA-SCRAM operations, which may begin as soon as the late 1990's, will rely heavily on semi-automated devices supported by manual or telerobotic set-up and manipulation (see Figures 3, 9, and 10). Eventually, however, artificial intelligence will enable fully-automated robotic EVA-SCRAM operations. The following eight scenarios will establish typical operational challenges which will have to be mastered.

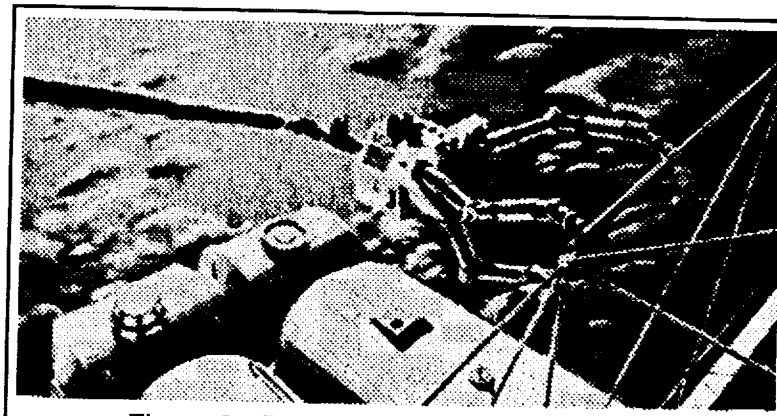

Figure 9 - Robotic SCRAM Operations

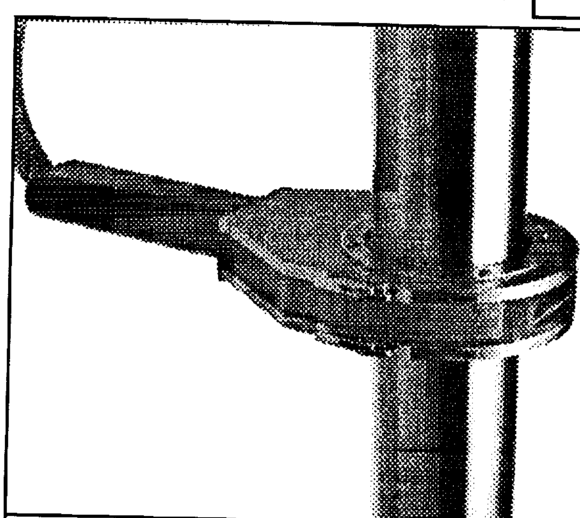

Figure 10 - Dimetric's Commercial GTA Semi-Automated Orbital Welding Device

Scenario-I: (Fluid Line Construction) - This scenario involves assembly of tubular lines or ducting which may be used for thermal control, propulsion, venting, life support, and laboratory supplies. The work-piece materials are likely to involve aluminum, stainless steel, titanium, and Inconel alloys. Due to standard geometries exhibited by tubular lines (varying primarily in diameter and wall thickness), most EVA-SCRAM operations (i.e. cutting, welding, NDE) in this scenario would be executed using semi-automated orbital devices which may be set-up manually or telerobotically (see Figures 3, 9, and 10).

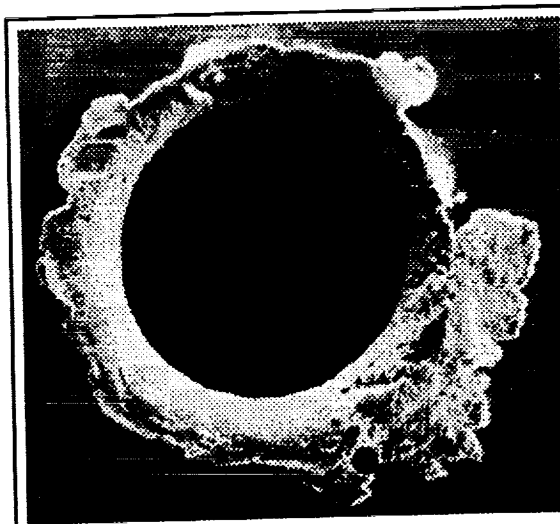

Figure 11 - 0.5 mm Diameter Puncture Found in a Spacecraft Louver

Scenario-II: (Structural Member Construction) - This scenario involves assembly of structural members which may be in the form of brackets, struts, beams, small truss, tubular extrusions, or plates. These members may be used for mounting equipment to the outside of the spacecraft, for routing and housing electrical lines (i.e. electrical conduit), or for shielding spacecraft systems. The work-piece materials are likely to involve aluminum, stainless steel, titanium, and Inconel alloys, and even composites. This scenario may involve both standard and non-standard geometries at the structural joints to be welded or cut. For standard geometries (i.e. involving tubular extrusions), semi-automated devices can be employed as described in Scenario-I. For non-standard geometries, automated joint seam-tracking may have to be employed using teleoperation, robotics, and artificial intelligence. Rockwell's Rocketdyne division has developed artificial intelligence capabilities integrated with robotics for complex welding tasks of Space Shuttle Main Engine components.

Scenario-III: (Orbital-Debris Puncture Repair) - This scenario involves repair of spacecraft surfaces and components which have been punctured by collisions with orbital debris. Punctures are most likely to be of small diameter, probably between 0.5 to 5 mm (see Figure 11); however, larger holes are possible. The workpiece materials are likely to involve aluminum, stainless steel, titanium, and Inconel alloys, and even composites. Punctures to pressurized systems (i.e. crew-laboratory module, radiator panel, fluid line, fuel tank) may require depressurization of the system prior to repair, due to interfering leakage. This type of repair scenario may employ SCRAM's surface preparation (i.e. cleaning, cutting) and welding and coating capabilities. Standardized circular patches may be employed with a semi-automated orbital device which would perform the repair operation after manual or telerobotic set-up.

Scenario-IV: (Atomic Oxygen Erosion Refurbishment) - This scenario involves re-coating spacecraft surfaces which have been eroded by atomic oxygen bombardment. Such surfaces involve thermal control radiators, telescope mirrors, electric conductors, and transmission or receiving antennae. The workpiece materials are likely to involve aluminum, stainless steel, titanium, Inconel, quartz, and various other materials. This scenario would most likely involve re-coating significant areas, lending itself to an automated operation. Very high dexterity motion (i.e. as with welding) would probably not be required. An automated robotic tool (i.e. like those used for spray-painting automobiles on a terrestrial assembly line) may be applied effectively with a manual or telerobotic set-up (i.e. using RMS).

Scenario-V: (Surface Cleaning) - This scenario involves cleaning spacecraft optical, solar collector, and 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 by exposure to the vacuum and ultraviolet radiation environment. These contaminants are also generated by spacecraft outgassing products, fuel, and propulsion by-products. This scenario would most likely involve cleaning significant areas, lending itself to an automated operation (similar to scenario-IV). Very high dexterity motion (i.e. as with welding) would probably not be required. An automated robotic tool (i.e. like those used for spray-painting automobiles on a terrestrial assembly line) may be applied effectively with a manual or telerobotic set-up.

Scenario-VI: (Large Orbital Truss Construction) - This scenario involves assembly of large truss structures by mass production welding and NDE of truss member joints (see Figures 1 and 12). The work-piece materials are likely to involve aluminum, stainless steel, titanium, and Inconel alloys, and even composites. For this scenario's repetitive and tedious mass production operations, automation is preferred. Truss members joints can be made suitable for automated EVA-SCRAM operations. For example, tubular truss members can be effectively welded and inspected with an orbital EVA-SCRAM device, like the one proposed for scenario-I (see Figure 10). To achieve full automation, however, the orbital device should be manipulated (set-up on the workpiece) by an autonomous robotic system with built-in artificial intelligence (see Figure 9). Less efficient truss construction can be achieved using telerobotic manipulation of the EVA-SCRAM device (i.e. using the RMS), or even manual manipulation. However, the actual joint seam tracking (i.e. for welding and inspection) will have to be accomplished using automation.

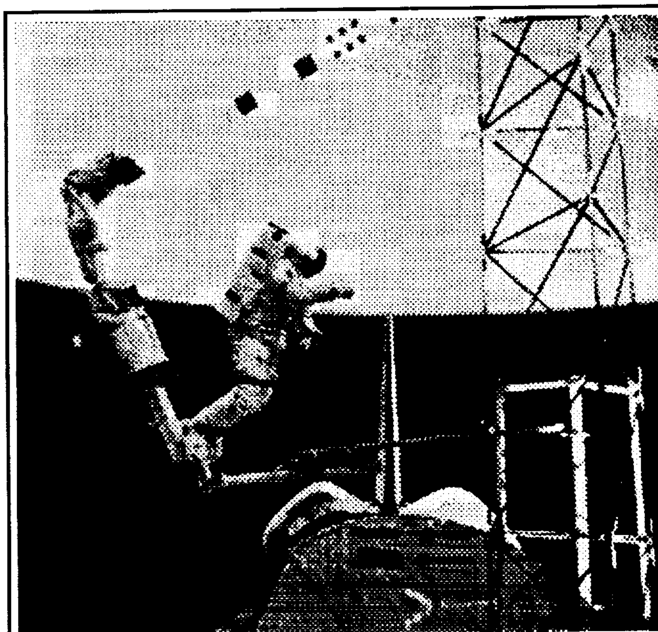

Figure 12 - On-Orbit Truss Assembly

Scenario-VII: (Aerobrake and Shadow Shield Construction) - This scenario involves assembly of large plated-structures by mass production welding and NDE of plate member joints (see Figures 7 and 8). The work-piece materials are likely to involve aluminum, stainless steel, titanium, and Inconel alloys, and even composites. For this scenario's repetitive and tedious mass production operations, automation is preferred. Plate member joints can be made suitable for automated EVA-SCRAM devices. To achieve full automation, however, the EVA-SCRAM device should be manipulated (set-up on the workpiece) by an autonomous robotic system with built-in artificial intelligence (see Figure 9). Less efficient construction can be achieved using telerobotic manipulation of the SCRAM device (i.e. using the RMS), or even manual manipulation. However, the actual joint seam tracking (i.e. for welding and inspection) will have to be accomplished using automation.

Scenario-VIII: (Lunar Outpost Construction) - This scenario involves a very important element which has been absent from the previous seven scenarios - gravity. The Moon's gravitational force, even though about one sixth of Earth's, will greatly facilitate EVA-SCRAM operations. The EVA-SCRAM operator no longer has to be tethered to the tools and attached, in one form or another, to a spacecraft. In addition, relative motion and position between the EVA-SCRAM operator and the workpiece will be simpler to control, since the Moon's gravity will bound both. Lunar EVA-SCRAM operations will involve various applications as described earlier, including 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 5-6). Work-piece materials are likely to involve aluminum, stainless steel, titanium, and inconel alloys, and even indigenous lunar produced metal alloys. Since the Lunar surface is still a vacuum-radiation hostile environment for EVA manned operations, execution of EVA-SCRAM tasks would emphasize teleoperation and automation over manual operations. However, some manual EVA support will always be required.

SCRAM PERFORMANCE AND SAFETY ISSUES

Designing an EVA-SCRAM system, requires that we consider the performance and safety of both the operator (i.e. astronaut, robotic device) and the mission (i.e. remaining crew, spacecraft, payloads).

EVA Crewmember Manual Performance Issues: Three major factors that may degrade EVA crewmember performance are extravehicular mobility unit (EMU) encumbrances, insufficient working volume, and inadequate restraints and mobility aids (see Figure 13). The EMU (space suit) is an independent anthropomorphic system that provides crewmembers with environmental protection, life support, mobility, communications, and visibility while performing various EVA's. The EMU incorporates a specially designed garment which can withstand high temperature, pressure, radiation, and physical wear. Consequently, the EMU limits the astronaut's manual dexterity and body movement. The EVA crewmember reaches fatigue levels much quicker than an operator (i.e. welder) on Earth; because delicate and precise hand movement require significant mental concentration and physical effort with the impeding pressurized space garment. Manual tasks such as the manual removal or replacement of threaded fasteners, continuous force-torque application, and extended gripping functions need to be minimized by the design of an EVA-SCRAM system (see Figure 14) [ref-1]. In addition, the EMU helmet impedes coordination and severely restricts visual examination of small-tight operations (i.e. welding). Because manual welding is a process which requires precision, coordination, and the ability to control several factors simultaneously (i.e. welding travel speed, welding arc gap, welding current output, and even welding filler wire feeding), the astronaut would have to be extensively prepared and trained for each single task. But, even then manual EVA-SCRAM welding operation may have low (20%) success rate, as can be expected of a comparable challenging terrestrial manual welding task. On Earth we accommodate the low success rate by simply cutting out the unacceptable weld and trying again; however, this would not be practical for space-based operations. Consequently, EVA-SCRAM operations must rely on the use of semi-automated devices, which would require relatively simple manual or telerobotic set-up. The EVA-SCRAM processes (welding, brazing, cutting, coating, cleaning, and NDE - see Figure 2) should be automatically executed with computer adaptive control, similar to existing terrestrial orbital welding systems (see Figure 15). These automated systems provide a 98% success rate. Therefore, manual EVA-SCRAM process execution (i.e. manual welding) should be reserved only for contingencies, where an automated system has failed or cannot be applied.

Figure 13 - Suited EVA Crewmember Employing a Portable Foot Restraint

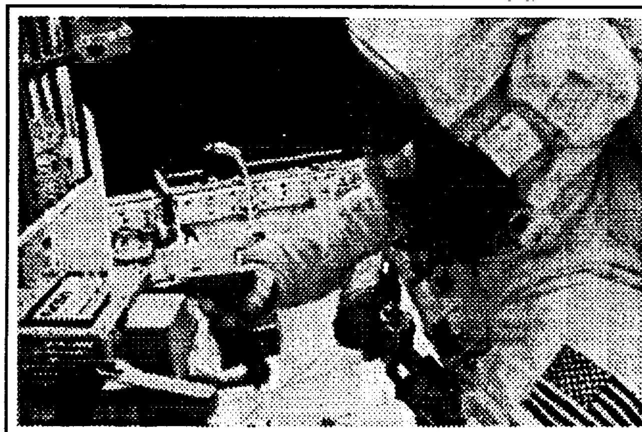

Figure 14 - Limited Manual EVA Dexterity

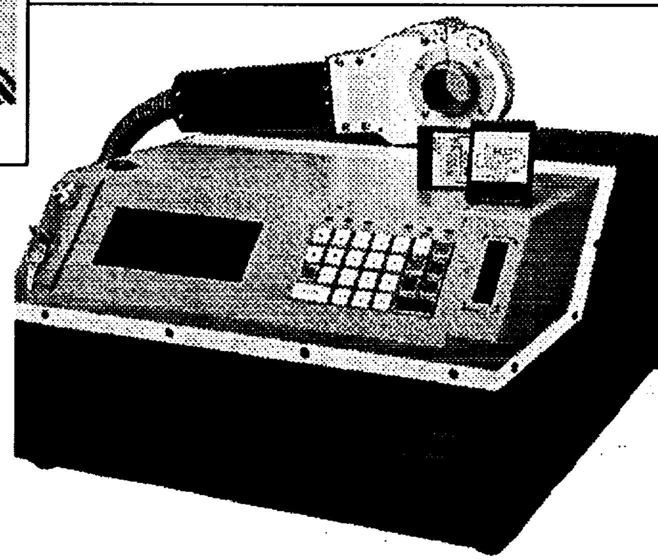

Figure 15 - Dimetric's State-of-the-Art Automated Programmable Welding System

Other Performance Issues: EVA-SCRAM operations will occur in both light and shadow (at 45 minute intervals in LEO) with consequent thermal gradients and sun-light reflections off of the workpiece. These dynamic factors will challenge operation of the EVA-SCRAM processes, requiring real-time electronic / optical sensor feedback and adaptive computer control in order to effectively perform routine SCRAM tasks. Robotic slave arms, such as the Shuttle's RMS with the Dextrous End Effector (DEE) and the Servicing Aid Tool (SAT), are incapable of the precision movement degree required for directly executing SCRAM's welding, brazing, cutting, and perhaps NDE processes. The robotic slave arms, however, should be capable of supporting telerobotic set-up and activation of a semi-automated EVA-SCRAM device (i.e. orbital welding head - see Figures 10 and 15).

Safety Issues: Safety of the spacecraft crewmembers and mission are of prime importance and, therefore, will govern the design of the EVA-SCRAM tool-kit and its operation modes. EVA-SCRAM's various tools and processes exhibit the following safety hazards: temperature extremes, electrical shock, contamination, and radiation. EVA-SCRAM's SWATT processes (electron beam, gas tungsten arc, plasma arc, and laser beam) are thermal tools which generate hot temperature extremes (i.e. a molten weld puddle). SWATT processes employ high currents or high voltages (depending on the process). Some of EVA-SCRAM's operations (i.e. welding, coating, cutting) produce varying levels of metal vapor which is redeposited on near-by surfaces. Lastly but not least, EVA-SCRAM's SWATT and NDE processes produce various levels and combinations of radiation (depending on the process), including: ultraviolet, infrared, extreme bright light, laser light, x-ray, accelerated electrons, and electro-magnetic interference. In summary, EVA-SCRAM is faced with various challenges of providing acceptable hazard inhibits and controls. SCRAM's terrestrial counter-part processes (i.e. welding) have been employed for years successfully, meeting safety requirements via various conservative safety measures and techniques. These terrestrial safety techniques and others can be modified to solve all of the safety issues associated with EVA-SCRAM.

Figure 16 - Former Soviet Union EVA Manual Welding Experiment

CONCLUSION

EVA-SCRAM is a leap into a new realm of on-orbit and even Lunar surface operations. By taking-on the challenge of EVA SCRAM operations, using the acceptable NASA safety approach, we will develop new critically needed tools for our upcoming space programs. The success of HST, EDO, LDO, SSF, and Lunar / Mars manned missions depends on the availability of EVA-SCRAM capabilities. On-orbit manual EVA-SCRAM experiments have already been initiated by the former Soviet Union (see Figure 16). EVA-SCRAM experiments should be continued with emphasis on productive operation modes, including: teleoperation, semi-automation, and full-automation. The EVA-SCRAM manual operation mode should be reserved for semi-automated device set-up and contingencies. EVA-SCRAM operations can be hazardous, especially if an EVA crewmember is present at the worksite. But, these hazards are containable. The nearest-term EVA-SCRAM applications which should be pursued, 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 which have been degraded by contaminants.

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