The Application of the Human Engineering Modeling and Performance Laboratory for Evaluation of Space Vehicle Ground Processing Tasks at Kennedy Space Center

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The introduction of United Space Alliance's Human Engineering Modeling and Performance Laboratory began in early 2007 in an attempt to address the problematic workspace design issues that the Space Shuttle has imposed on technicians performing maintenance and inspection operations. The Space Shuttle was not expected to require the extensive maintenance it undergoes between flights. As a result, extensive, costly resources have been expended on workarounds and modifications to accommodate ground processing personnel. Consideration of basic human factors principles for design of maintenance is essential during the design phase of future space vehicles, facilities, and equipment. Simulation will be needed to test and validate designs before implementation.

I. Introduction

Human factors is the science involved in understanding human capabilities and limitations for a given task in a given environment. For space flight applications, human factors designers seek to enable successful completion of tasks, ensure productivity of the mission, and provide a habitable living area for astronauts[9]. Similar objectives should apply for design of maintenance activities: designs should allow maintainers to complete tasks safely and efficiently without needing to choose between the safety of the hardware and their personal safety. Crew safety in the air depends on the quality of maintenance and inspection on the ground.

Because the quality of ground maintenance rests with the employees who execute the repair work, it is the responsibility of the designer to plan designs that will complement human capabilities and compensate for human limitations. The Space Shuttle maintenance environment was not designed around the maintainers. The level of effort and people performing the work were not thoroughly considered during the design phase. As a result, a reactive approach to design is necessary for fixing or mitigating the access, awkward postures, and transportation problems in flight hardware processing facilities.

United Space Alliance's (USA) Human Engineering Modeling and Performance Laboratory (HEMAP) is a new project being tested to help design processing tasks to make ground maintenance easier and safer to perform. It includes a motion capture system that captures human motions in an accurate, real-time 3D environment; and a human factors software package that performs various ergonomic analyses of high risk operations that involve heavy lifting, awkward postures, repetitive motions, and difficult reach positions.

The HEMAP Lab will help USA capture currently unknown, real-time human performance measurements for ground processing tasks. The goal of the HEMAP Lab project is to provide objective data that will give proper justification for safer, more efficient designs. It will provide a proactive approach for next-generation space programs by analyzing high-risk operations in initial design phases. The ability to simulate layouts, configurations, and operations before they are implemented will reduce exposure to hazards, injuries, and hardware damage and help workers understand and identify hazards before entering the processing environment.

This paper will discuss the human factors issues associated with maintenance activities and how the use of the HEMAP Lab can be used to better understand human performance in ground maintenance of human space vehicles. Applications of simulation for maintenance design will be discussed.

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II. Design for Maintainability

Incorporating human factors principles during the design phase of any product, task, or interface is fundamental for producing an error-free, user-friendly end product. Spacecraft designers are more aware of this today than ever. For long duration space missions in the future, a habitable, aesthetically-pleasing crew cabin will be needed to keep morale high and judgments rationale. Additionally, areas requiring crew on-mission inspection, maintenance, or repair must be designed to accommodate these tasks. Historically, the role of the human in these areas has been neglected. The result of omitting maintenance considerations in ground processing can be seen, as well, throughout ground processing facilities at Kennedy Space Center. Many improvements have been implemented to assist employees performing repair and inspection work on the Space Transportation Vehicles. However, the result of neglecting ground processing procedures in the design phase has been hardware damage, schedule impacts, and injuries.

For next generation space vehicles, the lessons learned from Shuttle processing need to be used to direct the design of new systems to prevent operational difficulties that have been a problem in past operations[8]. Designing for ease of maintenance will not only prevent operational difficulties, but also: will ensure reliability of systems, minimize personnel errors, reduce costs, optimize staffing[1], and reduce lost-time injuries.

The "Can-do" attitude of KSC ground processing personnel has resulted in many "homemade" creative solutions to accessibility and ergonomic issues in ground processing facilities. These solutions have significantly improved the way technicians and inspectors perform their work. There have also been significant industrial engineering or human factors improvements that have been implemented at the various ground processing facilities for risk reduction and efficiency improvements. Nevertheless, many of these improvements were only implemented after an incident had occurred.

One of the challenges facing technicians preparing an orbiter for flight is that there are areas containing hardware in the orbiter that were never intended to be frequently removed or require regular maintenance. As a result, these areas were not designed for human occupation, so workers are forced to maneuver their bodies to fit inside these areas, while being cautious where they step and place objects so as not to damage other hardware. To maximize efficiency and safety of processing, design of vehicle, facility, and equipment must be intertwined, ensuring safety of ground processing personnel and flight crews.

A. Design for Maintenance *and* Operation

Designing for maintainability is equally as important as design for operation. The two should be in equal balance. Basic characteristics to consider include access, ergonomics, and transportation. Simulation is needed to test and validate not only vehicle designs, but to ensure that the kind of maintenance that will be needed to sustain the vehicle will be safe, efficient, and cost effective. It is much simpler to change a design on paper than it is to change the hardware after it has been built.

Kennedy Space Center will be the primary site for assembling, launching, and maintaining next generation space vehicles. Designers need to learn from mistakes with Shuttle and perform tests to validate configurations before implementing them. Designers need to be provided with information that will allow them to design equipment and maintenance programs that will reduce human errors[2] that have resulted in accidents. To accomplish this, a partnership must be formed between vehicle, facility, and equipment designers. One cannot be designed before or after the other; vehicle design must consider ground maintenance, and facility design must consider the vehicle it will be servicing. The requirements for vehicle, facility, and equipment must be generated together. It is absolutely necessary for every design team to know each other's plans and requirements in order to avoid repetition of past errors.

The biggest human factors challenge facing designers is how to integrate human factors theories into everyday procedures and processes[5]. Total communication among all designers is absolutely critical to produce a system that will be safe, efficient, and cost effective. This concept seems simple and obvious; however, it can be easily forgotten. For future space vehicles, designing the vehicle first and designing maintenance systems later is not acceptable.

A thorough understanding of required maintenance is necessary before the beginning of the design phase. Although it is true the majority of maintenance errors are generally due to human error, maintenance errors are rarely due solely to an individual technician's mistake. Designers are taught about common maintenance errors, such as FOD (foreign object debris), confusion of parts, or incorrect installations or tools. However, there are usually deeper root and contributing causes to these errors. A maintainer who has been suitably trained on maintenance-friendly equipment, has well-written procedures, and has an unlimited amount of time will have a remote chance of making an error[3]. The chances of the maintainer making an error increase the more one is required to make inferences on what tools should be used and what methods one should follow.

There are numerous standards and design principles that describe factors that need to be considered when designing for maintainability. Simplicity of design is one of the most important aspects of designing for maintainability. Equipment design should be relatively obvious and minimize complexity[4]. If the design is simple and obvious, it will result in less time spent on maintenance and reduce the potential for an error.

B. Human Reliability and Risk Management

Human reliability can be defined as the use of system and human factors engineering methods to produce a comprehensive description of the human contribution to risk and to identify ways to minimize that risk[7]. Human reliability analysis (HRA) consists of various methods that describe human error in the context of Probabilistic Risk Assessment (PRA) or Probabilistic Safety Analysis (PSA). These tools are used to provide analytic, simulation, and predictive methods to describe human performance in complex systems[8]. Maintenance, however, has not received the same attention as operation. Much of the concentration on human performance in systems has not been focused on maintenance, assembly, or inspection but instead on how the human will perform during the operation of such a system.

Today at KSC, human reliability in ground processing is determined when something goes wrong; that is, the risk is resolved when it is manifest after an incident. The initial vision for Space Shuttle processing was that it would return from flight for a brief tune-up and head out the door again for its next flight. The reality of shuttle ground processing is that of a complex, maintenance and testing-intensive process after every flight for a vehicle that spends most of its life cycle on the ground. This costly, exacting, error-prone environment is directly attributable to the failure to consider human performance issues at the outset. The Space Shuttle consists of various complex engineering systems, from power generation and propulsion to environmental control. These systems are so complex that regardless of the thoroughness of ground maintenance crews, there is the possibility of a malfunction during flight because of the complexity of these systems[6]. Knowing the complexities of Shuttle, designers have the opportunity to produce a user-friendly maintenance system by recognizing and evaluating risks before implementing a design.

An excellent example of maintenance-friendly design can be seen with the design of the Boeing 777. Recognizing that maintenance may need to be completed in a short turnaround time, the 777 designers realized they needed a quick way of identification and isolation of failures, as well as good access to the equipment[10]. They used computer-aided human models to prove they would have good access for maintenance. They used computer screens to display fault messages to maintainers through built-in testing, and took time to ensure the information displayed was understandable, accurate, and prioritized problem areas. In addition, airline representatives would attend design reviews and meetings held by the engineering teams. This communication proved an excellent method for increasing reliability and maintainability[10].

Boeing points out that some things should take priority over others; that is, every single piece of equipment cannot always be made easy to fix, highly reliable and redundant because the cost of such an airplane would be extremely high. Therefore, Boeing created "design build teams" consisting of members from engineering, customer support, tooling, manufacturing, airlines, and suppliers[10]. As previously discussed, designing vehicle first, facility and equipment later will result in errors and low reliability. With Boeing's design build teams, the designers, builders, and supporters all worked together throughout the entire design phase. The airplane designers did not design the airplane and then simply hand it off for the maintainers to figure out how to sustain it. A partnership was developed. This is what needs to be done for the design of our next-generation space vehicles. The introduction of the first Chief Mechanic in 1990 for the design of the Boeing 777 is credited with playing a huge part in the user-friendly maintenance of the 777. Jack Hessburg, Chief Mechanic for the Boeing 777, stated that the "777 was built first for the line mechanic because he's the guy who signs the logbook and has to work in this tremendously time-driven environment."[10]

III. Simulation for Maintenance Validation

United Space Alliance has purchased an off-the-shelf motion capture system and human factors software in an effort to help vehicle, facility, and equipment designers design with human factors and maintenance in mind. Named the Human Engineering Modeling and Performance Laboratory (HEMAP) it is used to capture motions of personnel performing maintenance operations on space vehicles.

Originally purchased for the Space Shuttle Program, the HEMAP Lab is used to model tasks that put technicians in awkward postures or are particularly difficult for a human to perform. The current process requires the modeler to view, photograph, and videotape the actual task being performed in the real environment (picture "A" in the figure below). A mock-up is built in a lab environment to simulate the processing task, and a subject then puts on a black motion capture suit with silver markers strategically placed on the body to accurately capture motion using eight cameras surrounding the person performing the task (picture "B"). The motion is displayed real-time on a computer monitor using the motion capture software (picture "C"). The captured motion is then transferred to the human factors software package for ergonomic analysis and validation of design (pictures "D" and "E"). Current and proposed designs can be tested using the software.

Various tools are available for ergonomic analysis that account for duration of the task, repetitions, energy expended, and forces acting on the body. There are also tools for determining field of view, range of motion, and reach envelope. The software enables the designer to "size" the human in the environment to more accurately represent the size of the person who will be performing the work.

A proactive-reactive approach is currently used for modeling Shuttle activities. It is a proactive approach in the sense that hazards are being assessed to determine the risks associated and identify ways to control the risks. It is a reactive approach in that employees are already performing the processing task using a current design, and the task is being modeled after-the-fact. The ideal method of design would be to create a simulation of a task first and make appropriate changes as needed before hardware is built.

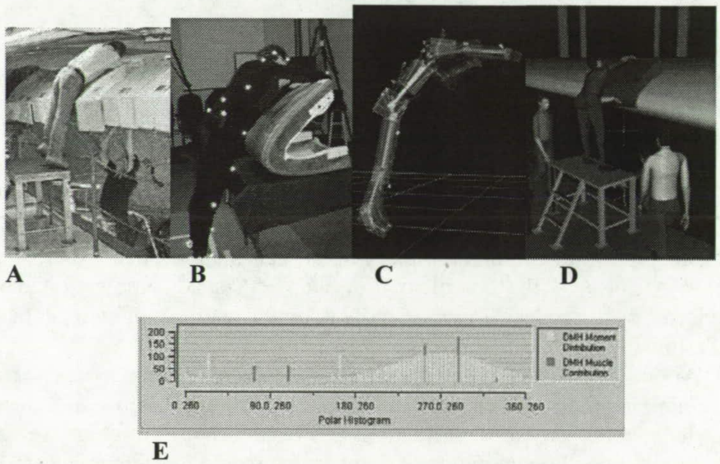

Figure 1. Flow of activities for Space Shuttle processing simulations. *This figure displays the flow of simulation activities for modeling the removal of an RCC panel from the orbiter wing leading edge.*

C. Project: Crawler Plywood

Several projects were "piloted" in the HEMAP Lab to examine its capabilities. The goal of these projects was to ensure the data generated would provide useful information for a designer to incorporate into his or her design. The first project involved the crawler transporter technicians.

The crawler transporter, used to transport the assembled Space Transportation System consisting of the external tank, solid rocket boosters, and orbiter vehicle, requires 400 sheets of plywood to be placed upon the launch pad surface so the twelve million pound transporter does not damage its track. The plywood is then hammered into place so it is secured to the pad surface. Because of injuries historically incurred performing this task, it was chosen to be a pilot project for the HEMAP Lab.

This project was used to validate the use of the Motion Capture hardware and Human Factors software in the lab. Task analyses that were performed include: Static Strength Prediction, which evaluates the percentage of the worker population that has the strength to perform a task based on posture, exertion requirements, and anthropometry; and Lower Back Compression Analysis, which evaluates spinal forces acting on the virtual human's lower back, under any posture and loading condition. As would be expected, the analysis proved that repeating this task 400 times will place an enormous amount of stress on a person's body. Knowing how performing this job will affect a person's body, improvements could be made prior to implementing a task such as this to minimize the impact on a person's

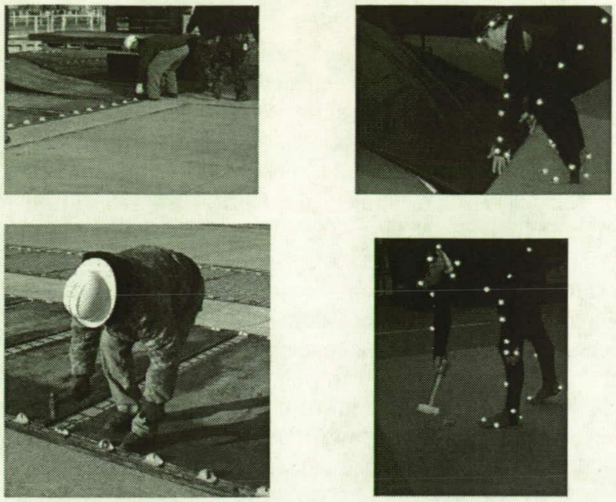

Figure 2. Laying and securing plywood for crawler path.

body. Possible improvements have been discussed that include incorporating a wire system to hold down the plywood instead of hammering each individual piece into place. A second improvement involves fabricating attachment pieces for the forklift that would "guide" the plywood into place so the human would not be required to maneuver it into place manually.

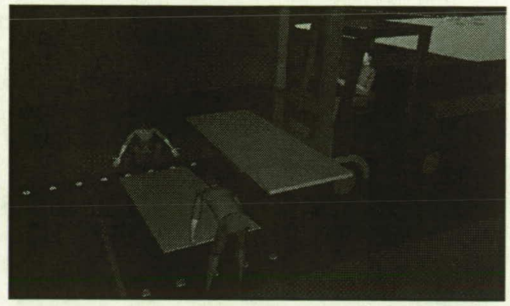

Figure 3. Human factors model of laying plywood on crawler path.

D. Project: Window Polycarbonate Cover Installation

The second pilot project performed in the HEMAP lab was the installation of polycarbonate window covers on windows seven and eight on the flight deck of the Space Shuttle. The need for these window covers arose from a concern regarding the use of camera equipment by the crew during flight. The concern was whether or not damage to a window resulting from camera impact could crack the window. Simulating window cover installation was chosen as a pilot project because an injury was incurred to an employee while practicing this task in the Space Shuttle simulator. The task required one person to hold the cover in place while another person built an adhesive barrier around him. The cover then needed to be held in place for 20-30 minutes while the adhesive dried.

Because of the configuration of the flight deck, the employee needed to arch his back in such a way to be low enough not to hit his head and also to avoid the panel behind him. This awkward posture combined with holding his arms over his head for an extended period of time to secure the polycarbonate cover resulted in an injury to the back. In addition to the ergonomic analysis tools used for the plywood project, additional tools were evaluated, including the Metabolic Energy Expenditure tool, which predicts metabolic energy expenditure requirements of a job based on worker characteristics and a description of the tasks that comprise the job; and the Fatigue and Recovery Analysis tool, which assesses whether enough recovery time is available for a given job to avoid worker fatigue.

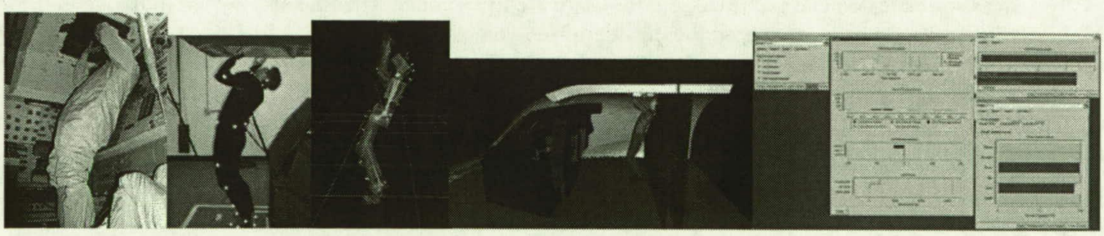

Figure 4. Simulation of window cover installation. *Flow of activities from observing the task through output analysis.*

As with the crawler plywood project, it is obvious this task would induce high levels of stress on the musculoskeletal system. It was chosen to demonstrate the value of simulation before performing the task in the actual environment. If the human part of this job was considered before the method was developed, this injury may have been avoided and ergonomic solutions could have been put in place prior to executing the task.

E. Project: Ingress/Egress through Orion Crew Hatch

This project was requested to examine the difficulty of carrying an item through the Orion crew hatch while entering and exiting the vehicle. This is the first project performed in the HEMAP Lab to evaluate a proposed design before its implementation.

The current design of the Orion Crew Exploration Vehicle is a capsule shaped much like that of the crew capsules used during the Apollo program; the base is a large circle with angled sides that narrow to form a cone with a smaller circle on the top. Given the proposed platform access to the crew hatch, a concern was surfaced regarding maintenance employees entering and exiting through the crew hatch while carrying objects. The proposed configuration for access to and from the vehicle consists of a platform on the exterior of the vehicle and a platform 31 inches below the bottom edge of the open hatch. Therefore, employees need to lower their head, side-step up and over to enter the vehicle, and also remain cautious of the 31 inch step down into the vehicle. It seems that entering and exiting through a door is and should be a relatively simple task. However, there have been injuries while performing the "simple" task of entering and exiting the Space Shuttle due to configuration for access. The workforce is aging and we must take into account the age and body type of the people who will be maintaining the hardware.

The first analysis performed was on the current proposed platform access to the crew hatch. Given the conditions described above, the simulation displayed how the employee would need to enter and exit through the crew hatch. The analysis allowed the lab team to evaluate the working posture of the individual using the available ergonomic tools and determine any risks associated with carrying objects into and out of the vehicle. Given the shape of the vehicle, the team brainstormed ideas for assisting employees into and out of the vehicle through the crew hatch.

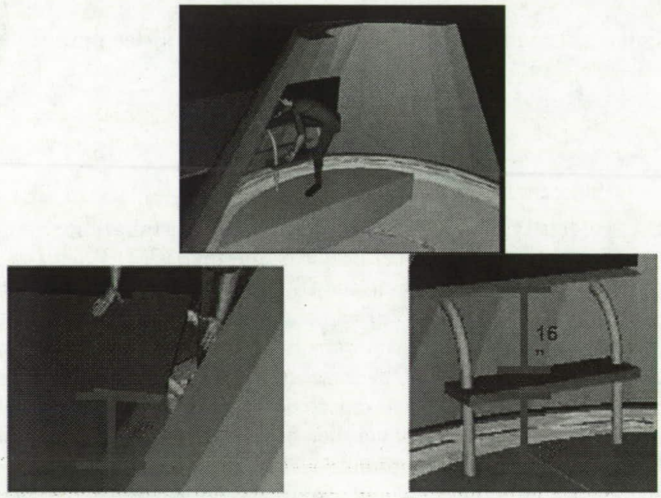
A B

Figure 5. Platform and step configuration for ingress/egress through Orion crew hatch.

One of the suggested improvements involved simply adding steps and handles for easier access. The ideas were created and imported into the software to visualize what the task would look like in the actual environment. By adding two steps, one on the outside of the vehicle (picture "A" in Figure 5) and one on the inside (picture "B"), it will allow slightly easier access through the crew hatch while carrying objects. Although neither configuration provides complete confidence that older employees will not have difficulty getting into and out of the vehicle, simulating the task and environment allows the designer to understand the conditions facing the maintainer, and make necessary improvements to ensure safety of our most valuable resource: the person.

IV. Conclusion

Simulation will prove an invaluable tool for evaluating vehicle, equipment, and configuration designs for next-generation space programs. Not only will it allow the designer to visualize how an employee will perform a task, it will allow the employee performing the task to identify any hazards before executing it. Simulating activities first will allow one to determine the optimal method for completion.

Processing for future vehicles such as Orion, the Crew Exploration Vehicle for the Constellation program, will greatly benefit from the use of simulation tools such as the HEMAP Lab. Not only will simulation allow the user to determine the optimal configuration for the work environment and proactively identify hazards, but it will also allow the user to perform pre-determined time studies for each operation. This will allow the designer to determine bottlenecks in the process and determine the necessary process flow reduction needed.

Simulating human activities will allow the designer to understand the effect of an activity on a person's body over time. Understanding activities that can cause cumulative trauma disorders will help reduce cost associated with injury and reduce worker fatigue, which leads to loss of productivity and decrease in morale. Designing for comfort and range of motion will significantly reduce the probability of making an error while performing maintenance.

Designing space vehicles for maintainability and repair-ability is equally as important as designing for operation. Vehicle, equipment, and facility designers need to work together to produce a maintenance-friendly environment on the ground that will ensure crew safety and productivity during flight. Using simulation tools such as the HEMAP Lab will enable designers to describe and evaluate human performance in the maintenance and operation environment. Proactively identifying risk will increase the efficiency of the design process and reduce mishaps and lost time injuries.

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References

[1]Sandia National Laboratories, *Center for System Reliability*, URL: http://reliability.sandia.gov/index.html.

[2]Department of Energy Handbook 1140-2001, "Human Factors/Ergonomics Handbook for the Design of Ease of Maintenance," U.S. Department of Energy, Washington, D.C., 2001.

[3]Mason, S., *Improving Maintenance—A Guide to Reducing Human Error,* HSE Books, London, 2000.

[4]National Aeronautics and Space Administration, "Man-Systems Integration Standards," NASA-STD-3000, Vol. 1, Rev. B, 1995.

[5]Space Shuttle Independent Assessment Team, "Report to Associate Administrator of Space Flight," National Aeronautics and Space Administration, 2000.

[6]McCann, R.S., and McCandless, J., "Toward a Crew System Concept for Real-Time Fault Management in Next Generation Aerospace Vehicles," *Proceedings of the 2nd Modeling and Simulation JANNAF Subcommittee Meeting,* Sandestin, FL, 2002.

[7]Basnyat, S., Bernhaupt, R., Boring, R., Palanque, P., and Johnson, C., "Testing Interactive Software: A Challenge for Usability and Reliability," *Special Interest Group—CHI 2006,* Montreal, Canada, 2006.

[8]Nelson, W.R., "Integrated Design Environment for Human Performance and Human Reliability Analysis," *IEEE Sixth Annual Human Factors Meeting,* Orlando, FL, 1997.

[9]Mount, F.E., and Foley, T., "Assessment of Human Factors," *Extended Duration Orbiter Medical Project,* National Aeronautics and Space Administration, DSO 904, 1996.

[10]Knezevic, J., "Chief Mechanic: The New Approach to Aircraft Maintenance by Boeing," *Journal for Quality in Maintenance Engineering,* Vol. 5 No.4, 1999, pp. 314-324.

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This paper discuss the use of the Human Engineering Modeling and Performance Lab for simulating maintenance activities at KSC. It discusses the importance of simulation and three projects that have been performed.

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