Proceedings of Space 90, Engineering, Construction, and Operations in Space, Vol. 1,
Edited by S. W. Johnson and J. P. Wetzel, ASCE, New York, 1990, pp. 226-235.

Automation and Control of Off-Planet Oxygen Production Processes

W. J. Marner[1], J. W. Suitor[2], L. S. Schooley[3], and F. E. Cellier[4]

Abstract

This paper addresses several aspects of the automation and control of off-planet production processes. First, a general approach to process automation and control is discussed from the viewpoint of translating human process control procedures into automated procedures. Second, the control issues for a specific process, namely the automation and control of off-planet oxygen processes, are discussed. Sensors, instruments, and components are defined and discussed in the context of off-planet applications, and the need for smart components is clearly established. Finally, the automation issues and operational philosophies required in such a plant are summarized.

Introduction

The processing of materials on an extraterrestrial surface requires substantially more automation and control than materials processing on the Earth's surface. The demands on astronaut personnel by other activities and the limited number of available operators, places a requirement of near autonomous

[1]Group Supervisor, Instrument Research Group, Jet Propulsion Laboratory, California Institute of Technolgy, 4800 Oak Grove Drive, Pasadena, CA 91109.

[2]Group Supervisor, Thermal Power Conversion Group, Jet Propulsion Laboratory, California Institute of Technolgy, 4800 Oak Grove Drive, Pasadena, CA 91109.

[3]Associate Professor, Electrical Engineering and Computer Science, University of Arizona, Tucson, AZ 85721.

[4]Associate Professor, Electrical Engineering and Computer Science, University of Arizona, Tucson, AZ 85721.

operation on such processing facilities. The extremes in environmental conditions such as hard vacuum, high and low temperature, and radiation effects complicate the situation further. However, the current state of the art does not permit execution of complex operations in hostile environments with an acceptable probability of success. Therefore, additional work will be required in those areas where adequate automation and control technology do not presently exist.

Off-planet materials operations have been automated on Earth; however, the requirements for automation far away from manual help and in hostile off-planet environments will require substantial changes in automation technology. This paper addresses two aspects of off-planet automation processes. First, a general approach to process automation and control is discussed from the viewpoint of translating human process control procedures into automated procedures. Second, the process-specific control issues for a particular process, namely the automation and control of off-planet oxygen processes are discussed.

Perhaps, the best way to understand the necessary requirements to automate a lunar or Martian oxygen production plant is to consider the functions which the typical plant operator does here on Earth at a typical processing plant such as an oil refinery. The operator makes routine rounds of the equipment to see that all is in working order and checks all instrument readouts to assure that the desired operating conditions are within acceptable operating tolerances. Logs and reports of the activities are maintained systematically and there is a constant alertness to those moments when trouble develops in the plant. In an alarmed situation, i.e., a situation where an instrument or component has become uncontrolled and operator intervention is required, the experienced plant operator knows the specific steps and their order to remedy the problem. Usually, the first step is a confirmation that the instrument readout is indeed correct and that there is a problem. Often this is done by checking other instruments to confirm that their outputs agree with the existing conditions. Computations may have to be made to determine if the readout is accurate. An emergency condition may require immediate action to prevent damage to other equipment or disaster before such computations are made. Once the operator has confirmed the problem, a planned course of action is developed and carried out. In general, the approach used is very systematic and logical although there are numerous situations where the creativity and imagination of the plant operator is essential in overcoming the difficulty. In such instances, logic means very little.

The control procedures exercised by an operator in an Earth-based processing plant can be summarized by a set of attributes similar to those expected in an automated off-planet processing plant. These attributes include:

- Constant health monitoring of local subsets of the process
- Computational capability to compare actual conditions with desired set points
- Reporting capability to a master control system
- Rule-based system for determining response to a process upset
- Ability to confirm calibration of measuring instruments
- Ability to protect the rest of the process during system upset
- Ability to communicate emergency information and call for help if required.

These attributes translate into a number of requirements of an automated processing plant including:

- Use of expert systems
- Having major data buses with high data rates
- Capability of remote and local control
- Capability for operation during unmanned periods
- Telerobotics and autonomous robotics for inspection and repair
- Smart components
- Modularity and interchangeability of all components
- Provisions for in-situ calibrations by utilization of intrinsic, natural, or embedded standards
- Evolutionary systems.

Expert systems will be required because of the high degree of complexity and low level of manned presence on the lunar or Martian surface. Additionally, the high data rates required for close monitoring will also dictate an automatic or possibly autonomous control system. There will also be the probability of remote operation from earth, low earth orbit (LEO), or the manned base that dictates the need for an expert system to comprehend the control source and provide the necessary interlocks to prevent dual operational attempts from two sources.

Coupled with the need for automatic operation is the need for robotic devices to be used for materials handling and the replacement of parts. According to Sheridan (1988), robotics may be defined as "the science and art of performing, by means of an automatic apparatus or device, functions ordinarily ascribed to human beings, or operating with what appears to be almost human intelligence." *Robot* ordinarily implies autonomy, with essentially *no* human interaction. However, the current state-of-the-art of robotic devices is such that the possibility of complicated repairs by means of robots is not very likely. But the use of robots for replacement of defective components is well suited for parts that are interchangeable and modular. Modularity allows operation at a reduced level of performance to continue while one of the modules is being replaced. Such interchangeability is required to keep the number of spare parts to a minimum. Closely related to this philosophy of replacement is the concept of redundancy. There are trade-offs between replacement and redundant systems which will require further study.

The principal issue faced by the designer of off-planet materials processing plants is the translation of that Earth-based plant operator know-how into a computer based automated system. In order to do that, there are several issues that must be addressed including:

- Component systems that supplant operator presence
- Complete knowledge of the operational characteristics of the process being controlled
- Measurement systems designed for the specific process used
- Control strategy that includes the process specific sensitivities to control conditions
- Redesign of the process to best utilize automation and robotic capabilities.

Obviously, the nature of automation and control of off-planet materials processing requires a detailed knowledge of the process to be controlled. However, the component systems used to replace operator presence are more generic in nature and are called smart components. Some of these smart components have the ability to perform self health evaluations and maintain some degree of self data handling for a distributed data system.

Another aspect of the automation process which must be taken into consideration is the issue of simplicity versus robustness, i.e., the system must be as simple as possible yet reliability is of utmost importance. Robust may be defined as "having or exhibiting strength or vigorous health", or as "strongly formed or constructed." Unfortunately, robustness and simplicity are in competition with each other. In order to make a sensor or a controller failsafe, it is necessary to add components to it which allow it to recognize its own malfunction and to switch to a backup component if necessary. Such a design makes the system more robust, but simultaneously adds to the overall system complexity. Off-planet oxygen production processes will have to rely heavily on smart sensors, controllers, and components, much more so than for similar equipment used on Earth at the present time. Therefore, in order to ensure that this equipment is adequately robust, it most certainly will be much more complex.

Process Control Issues

On the surface of the moon the hydrogen reduction of ilmenite approach for producing oxygen has been researched and described in several funded efforts. The production of oxygen on the surface of Mars would probably be less complicated since the oxygen could be removed directly from the CO_2 atmosphere which is in plentiful supply. Although the ilmenite process is not the only one for producing oxygen on the surface of the moon, it does serve to illustrate the process-specific requirements for automation and control of oxygen production, and the remainder of the paper will focus on this process.

A schematic of this process is shown in Figure 1. Lunar ilmenite ore is placed in a high temperature (800-1000 C), high pressure (> 10 atm) reactor. Hydrogen is sparged through the ore as a fluidized bed and reduces the ilmenite, $FeTiO_3$, to elemental iron, TiO_2, and steam. The hydrogen-steam gas mixture exits the reactor where the fines from the ore are removed in a cyclone separator. The steam is electrolyzed in a high temperature electrolysis unit where oxygen is removed and sent to a liquefaction unit, and the hydrogen is returned to the reactor. A heat exchanger is used to cool the hydrogen so it can be recompressed and then the gas is heated before it returns to the reactor.

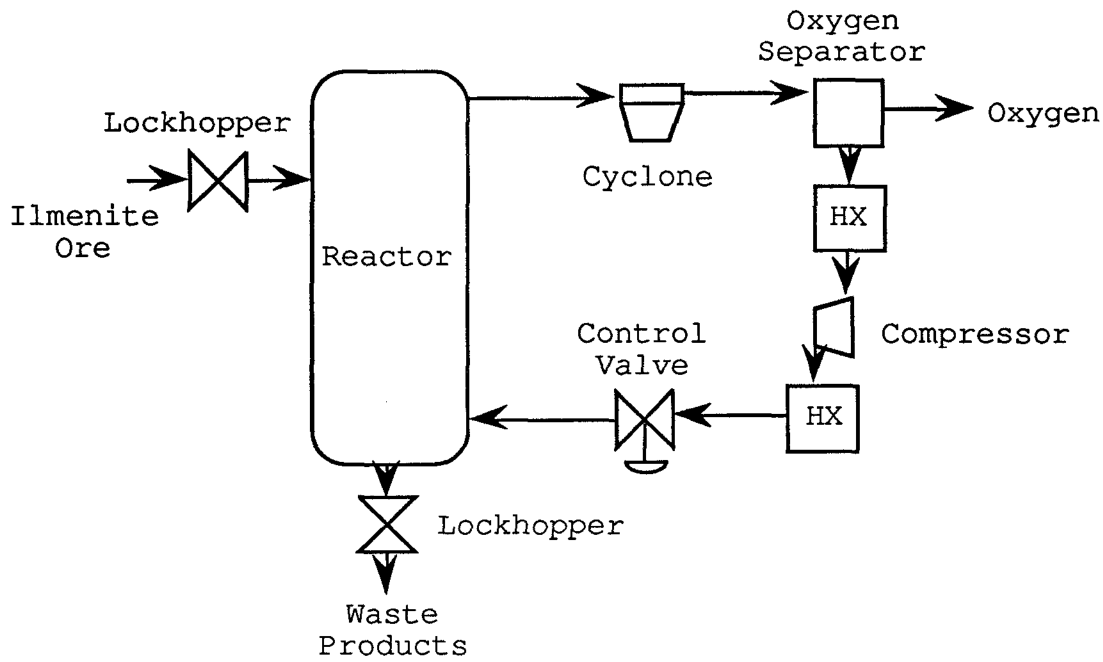

Figure 1. Hydrogen Reduction of Ilmenite

The process using hydrogen reduction of ilmenite has a number of process specific issues that require special attention for automation. It will be necessary to feed the ilmenite into the reactor by means of a lockhopper if the process is to operate on a semicontinuous basis. Waste material will be removed from the reactor by a similar lockhopper. Both lockhoppers will be subject to wear and leakage of the pressure seals as well as jamming due to large particles. Monitoring equipment and control strategies will have to be developed that reflect the needs of the process and the lockhoppers.

The fluidized bed operation presents some special challenges. The bed in the reactor, including the fluidization level, height, and temperature, must be monitored to prevent the ore charge from sintering and becoming a solid plug of material. Also, the carryover from the reactor must be measured to determine the solids loading on the cyclone, and the removal efficiency of the cyclone must be monitored to prevent carryover of fines to the electrolysis unit.

Of course, a detailed study will have to be carried out to design a complete control system for the oxygen process described. However, from this brief discussion some of the major issues have been identified and will provide the basis for a further discussion of sensors, instruments, and components.

Sensors, Instruments, and Components

In order to understand the concept of smart components, it is important to differentiate among sensors, instruments, and components. *Sensors* are the most primitive elements of the automation and control structure and consist of such items as thermocouples and pressure transducers. *Instruments* utilize sensors to make measurements required for process control and include, for example, flowmeters, corrosion meters, and chemical composition measuring devices. *Components* are a collection of devices that actually implement the control of the process. These components make up a small subsystem of the plant and utilize sensors and possibly instruments as a part of their operation, control, and automation. Such components include valves, heat exchangers, reactor vessels, compressors, pumps and related equipment.

As the smallest subset, sensors are the basic building blocks of both instruments and components. There are some specialized types of sensors but those utilized for temperature and strain measurement are among the best known. Temperature measurements are generally made by either Seebeck devices (thermocouples) or resistive devices (resistance thermal detectors or RTDs). The obvious use of these types of sensors is in the measurement of temperature although they could also be used for the detection of other conditions such as radiator surface contamination when used as a heat flux meter. Strain measurements are based on a change in resistance when a displacement is imposed on an element. Such sensors are used to measure force or displacement and are usually found in pressure and differential pressure transducers. Force measurements would be used for weight measurement or possibly solids flow. Sensor technology is reasonably well developed except in the case of specific chemical sensors associated with integrated circuit technology.

A number of instruments will be required for off-planet oxygen production processes. Some of these are fairly standard and are discussed in standard references such as Considine (1974), while others are considerably more complex. Instruments required for oxygen production will include a thermograph, a video monitoring system, several flowmeters, a solids level indicator, corrosion meters, and chemical composition sensors.

A plant that is nearly autonomous will require a high degree of automation, including self calibration, health monitoring, and data communication among the various components. It is therefore necessary to have components in the system that are "smart." A smart component is one that monitors its own operation and has electronic attributes that allow it to become part of a distributed computer controlled system. Each component will be endowed with a microprocessor that interrogates its important subfunctions, determines that these subfunctions are within predetermined nominal operational limits, performs self-calibrations and other limited health checks, and communicates to the rest of the control system through a data bus. The data communication linkage allows the component to call for help when needed and permits the master operating program to interrogate the smart component. The linkage also allows for intervention by the operating program as well as from local at-plant control and remote on-earth consoles.

As an example, consider a smart control valve which regulates the mass flowrate of a fluid by adjusting an orifice through which the fluid flows. The general construction of a control valve consists of a rod or stem that has a variable cross section on one end to change the flow area through the valve. A seal is placed around the stem where it enters the valve body, thus providing a pressure barrier between the fluid and the surrounding environment. The stem is moved by an actuator that, for off-planet purposes, is an electric stepper motor and gear box. A smart control valve will make measurements of stem position and/or actuator position, packing leakage, and valve pressure drop.

The stem or actuator position measurement is intended to let the local controller know that the stem is in the proper position for the control setting sent to the actuator. Improper position would indicate a failure of the actuator or a blockage of the stem in the valve body. Valve pressure drop measurement would verify if there was a valve blockage, suspected from either an improper stem setting or from a drop in measured flowrate. Packing leakage would identify the failure of the packing seal around the stem and the need for repair or replacement.

Sensors required for these measurements include a variable potentiometer for stem/actuator position, differential pressure transducer for valve body pressure drop, and either a thermocouple or a chemical composition sensor for the packing stem leak. The thermocouple could be used if there was a significant temperature difference between the leaking gas and the local environment, or if the chemical sensor was tuned to the gas composition leaking from the packing stem.

Other smart components for the ilmenite process include heat exchangers, cyclones, lockhoppers, and compressors.

Conclusions

Oxygen processing plants located off-planet Earth will require considerable automation and control without human interaction. The demands placed on man-tended off-planet operations, balanced with the cost of such operations, prevent the consideration of man-tended oxygen processing plants and place greater emphasis on automated operations. Automation issues that must be considered include:

- Detailed knowledge of the operation and potential faults of the process
- Specification of the allowable tolerances for various measurements
- Methodology and instrumentation requirements for maintenance and health monitoring
- Self calibration of sensors and health verification
- Duplicity of instrumentation and control elements

Clearly, the philosophy by which an automated oxygen processing plant is to be designed and operated must be established early in the development of the plant and needs to be considered when contemplating the issues that such a plant must face. Some of these operational philosophies include:

- Use of expert systems
- Major data buses with high data rates
- Ability to have both local and remote operation
- Capability and high reliability over long periods of unmanned operation

- Telerobotic and autonomous robotic capabilities for inspection and repair
- Smart sensors and components
- Modularity and interchangeability of parts
- Provisions for in-situ calibrations by utilization of intrinsic, natural, or embedded standards
- Evolutionary systems.

Sensors, instruments, and components provide the tools by which the measurement and control of an automated system is accomplished. Sensors are the most primitive elements of the automation and control structure and include such items as thermocouples, flow meters, and pressure transducers. Instruments utilize sensors to make measurements required for process control decisions and diagnostics of potential problems. Finally, components are a collection of devices that actually implement a control process. These components make up a small subsystem of the plant and utilize sensors and instruments along with the master control program or expert system to control the processes in a desired way.

Probably the area of greatest potential impact on automated off-planet processes is that of smart components. Such components have the ability to monitor their own operation, diagnose any existing problems, and obtain solutions to these problems. The monitoring, diagnosis, and response functions require the component to have a set of sensors designed to monitor operation, a microprocessor-based expert system to consider most likely errors and responses, communication capability to respond to a master control system when requested, and request help when needed. The technology development needed in this area requires the merging of existing components with sensors and expert systems that will allow the system to operate effectively with artificial intelligence.

References

Considine, D. M., Editor-in-Chief, 1974, *Process Instruments and Controls Handbook*, Second Edition, McGraw-Hill, New York.

Sheridan, P. B., 1988, "Supervisory Control of Telerobots," *Machine Intelligence and Autonomy for Aerospace Systems*, Edited by E. Heer and H. Lum, American Institute of Aeronautics and Astronautics, New York.