

Supercritical water oxidation: An emerging technology*

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Abstract

Environmental constraints continue to force the chemical-petrochemical industry to seek new technologies to process waste streams. The treatment of dilute aqueous streams containing hazardous organic substances has always presented both technical and economic challenges. The MODAR Supercritical Water Oxidation (SCWO) process meets these challenges. The MODAR process for hazardous waste destruction operates at nominal conditions of 600°C and 23 MPa. Under these conditions, organic compounds are completely miscible with supercritical water and with oxygen and nitrogen, and can be rapidly oxidized to CO₂ and H₂O. Inorganic salts, on the other hand, exhibit sharply reduced solubilities, and to a large extent precipitate at reaction conditions. These physical and chemical phenomena lead to an implementation of the MODAR process wherein hazardous wastes are oxidized and inorganic salts are separated in a single reaction vessel. The process is capable of achieving high destruction efficiencies of hazardous organic constituents in excess of 99.99% in a single step. The process precludes the formation of the primary pollutants, NO_x and SO₂, and accommodates *in situ* acid gas neutralization. The basic chemistry and operating parameters of the process were developed by MODAR, Inc. in bench- and pilot-scale operations. More recently, scale-up issues have been identified and addressed in a cooperative engineering development program between ABB Lummus Crest Inc. and MODAR, Inc. The results of this development program have produced a basis for design of commercial plants. This development program and key features and concepts of the design are highlighted in this paper.

Introduction

Waste organic compounds are oxidized in the MODAR Supercritical Water Oxidation (SCWO) process at moderate temperature and high pressure in a medium of supercritical water. Operating conditions preclude the formation of

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the primary pollutants, NO_x and SO_2 , and accommodate *in situ* neutralization of the produced acid gases. Inorganic salts thus formed (as well as salts present in the initial waste feed stream), precipitate in the reaction medium, and can be separated in a single reactor/separator vessel.

Interest in this waste treatment technology has increased dramatically in recent years, with universities, research institutes, and United States national laboratories and government agencies conducting research in the field. Tester et al. [1] have written a review of the fundamentals of SCWO technology including a discussion of research on reaction kinetics, phase equilibrium and solid salt separation. A comprehensive review of the technical and patent literature is included therein. MODAR and ABB Lummus Crest Inc., the latter the world-wide, exclusive licensor of the patented MODAR SCWO process, are actively pursuing commercialization of the technology.

The focus of this paper is on the engineering development conducted jointly by MODAR and ABB Lummus Crest in support of establishing a commercial design. The most challenging scale-up and engineering design issues are reviewed, and the technical programs completed to establish a basis for design are described. General process options are also discussed.

Process fundamentals

Supercritical water oxidation reactions are carried out above the critical point of water, which is 374°C and 22.1 MPa . It is well known that water above its critical point is an effective solvent for organic compounds. In addition, gases including oxygen are completely miscible in the fluid. Thus, a homogeneous, single phase results when organic compounds and oxygen are dissolved in supercritical water, and the reaction process proceeds without interfacial mass transfer limitations. A reaction time of less than 10 seconds at typical process conditions of 620°C and 23.5 MPa is needed to achieve 99.99% destruction of the organics.

Reaction products of organic oxidation are carbon dioxide and water. Carbon monoxide concentration in reactor effluent is typically under 50 mg/m^3 , and SO_2 and NO_x emissions are generally on the order of 1 mg/m^3 . Organic heteroatoms are converted to inorganic compounds, usually acids, salts or oxides. Sulfur is converted to sulfate, phosphorus to phosphate, and halogens to haloacids. Compounds containing nitrogen, regardless of its oxidation state, are oxidized to N_2 and N_2O (nitrous oxide), and not to NO_x because of the relatively low reaction temperature.

Except for acids such as H_2SO_4 and HCl , inorganic compounds are only slightly soluble at typical SCWO conditions. The acids can be neutralized *in situ* to form salts which subsequently precipitate from the hot fluid. Any inorganic salt or oxide, whether initially present in the influent waste water or formed by chemical reaction, will, to a large extent, precipitate at reaction

conditions. In general, precipitated oxide solids have been found to remain non-sticky and flowable, while salts, particularly those containing chloride, sulfate or carbonate, tenaciously adhere to solid surfaces with which they come in contact. This latter fact has driven the development of a reactor configuration to handle sticky salts such as sodium chloride and sodium sulfate, which are common to most industrial wastewaters.

Reactor configuration

The simplest reactor configuration is a tubular (pipe) reactor, and is applicable to waste feeds yielding very low salt concentrations or generating salts and solids which have good (i.e., non-sticking) flow properties. This type of reactor should always be considered if free flowing solids can be achieved at reaction conditions. Waste streams not meeting this criterion lead to salt accumulation, solids bridging and eventual plugging of a pipe reactor. It has generally been our experience that the free-flowing salt condition is seldom satisfied for actual industrial waste streams.

A patented vessel reactor method [2] for handling sticky salts has been developed and will be the focus in this paper. Here, a single pressure vessel is utilized for oxidation of organic materials and separation of (solid) inorganic materials from the fluid. A vertical, cylindrical vessel (see Fig. 1) consisting of two zones, is used: A supercritical high-temperature zone and a lower temperature zone. Pressurized feed material and oxidant are injected downward by means of a co-axial nozzle into the hot zone located in the upper portion of the vessel. Oxidation of the organics and oxidizable inorganics takes place in this supercritical temperature zone, and gaseous effluents from this phase undergo a reversal in flow direction and are discharged from the top region of the vessel. Insoluble material, usually inorganic salt, that is initially present or formed in the supercritical fluid phase forms dense brine droplets or solid precipitates which inertially impinge on, and fall by gravity into, a liquid phase maintained in the bottom portion of the reactor by injection of cold water. The bottom low-temperature liquid phase provides a medium for trapping contacting solids, for dissolving soluble salts, and for forming a slurry of insoluble materials. The resultant brine solution or slurry is removed from the pressure vessel via a discharge nozzle located in the lower zone of the vessel.

The characteristic feature of the method is that solids in contact with the supercritical temperature process stream are transferred to a liquid phase in the cooler zone within the same vessel, still at elevated pressure, to form a brine slurry. This technique is the basis for removing solids from the high temperature, high pressure process stream.

The vessel reactor has been tested under continuous flow conditions in laboratory and pilot reactors of 71 mm and 254 mm internal diameter, respectively. The configuration of the pilot reactor, shown in Fig. 1, indicates relative

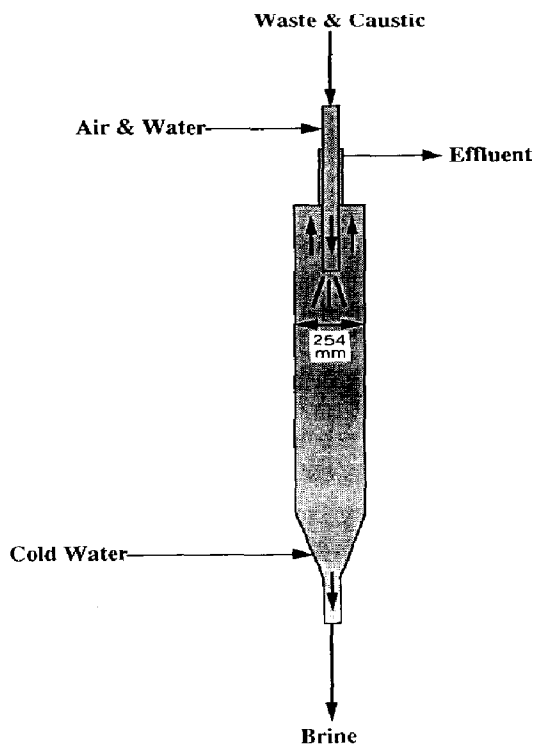


Fig. 1. Configuration of pilot plant reactor.

geometry and the location of feed and discharge nozzles; a similar configuration has been used in the laboratory. Each unit has successfully oxidized a wide variety of waste feed materials, including aqueous solutions with a wide range of heating values, two-phase liquid mixtures, pure organics and fuels, both organic and inorganic particulate slurries, and chlorinated hydrocarbons using *in-situ* neutralization with sodium hydroxide. Oxidation of these various organic materials has been unequivocally established in the laboratory and pilot plant systems, with destruction efficiencies generally on the order of 99.99% or greater [3,4]. The indiscriminate destruction of organic species is illustrated in Figure 2 which shows gas chromatograms (using a mass spectrometer detector) generated in the pilot plant for an industrial waste stream and the corresponding treated effluent stream. The wastewater contained a complex mixture of organics including many common chlorinated and non-chlorinated industrial solvents. Although the chromatogram peaks were not specifically identified, each represents an individual compound. Identical detection limits of 1 ppm (v/v) were used in both chromatograms. The reduction of the organic components is readily apparent. Reaction conditions were 620°, 23.5 MPa with a residence time of less than one minute.

One important aspect of the reactor is the axial temperature and density gradients achieved from the hot oxidation zone to the cool solution zone within

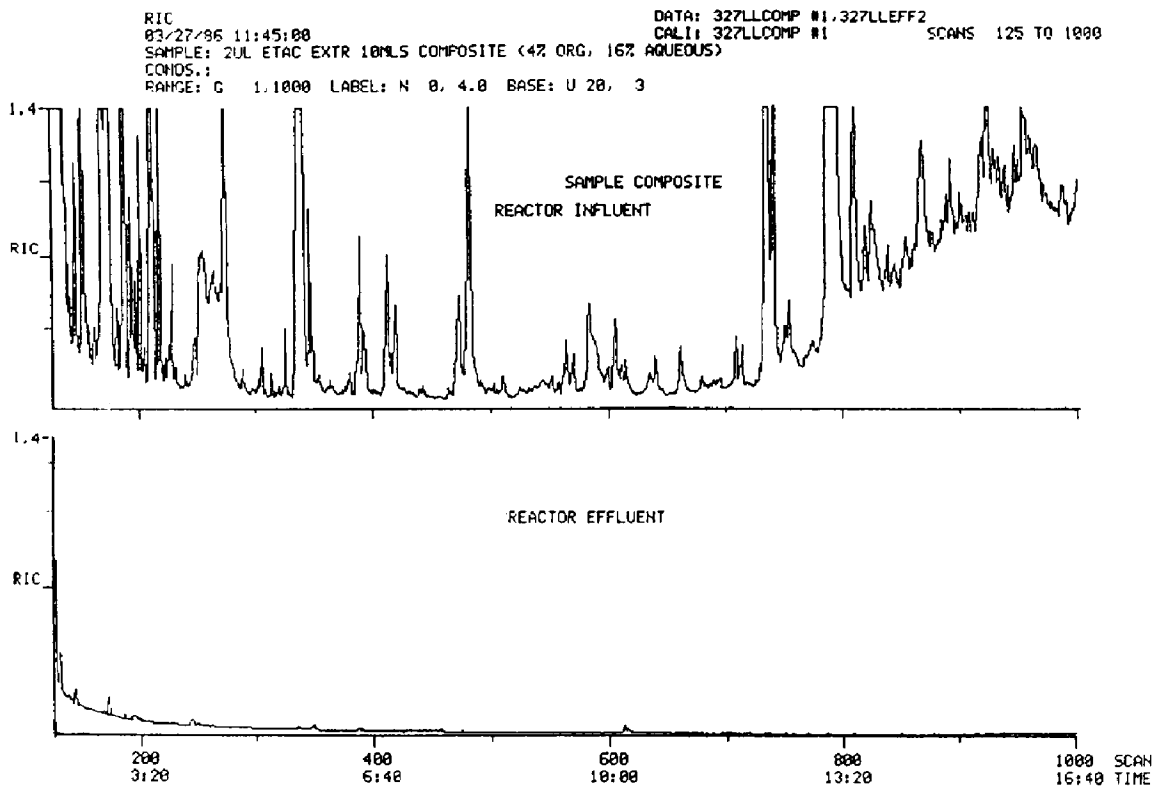


Fig. 2. Chromatograms from pilot plant operation.

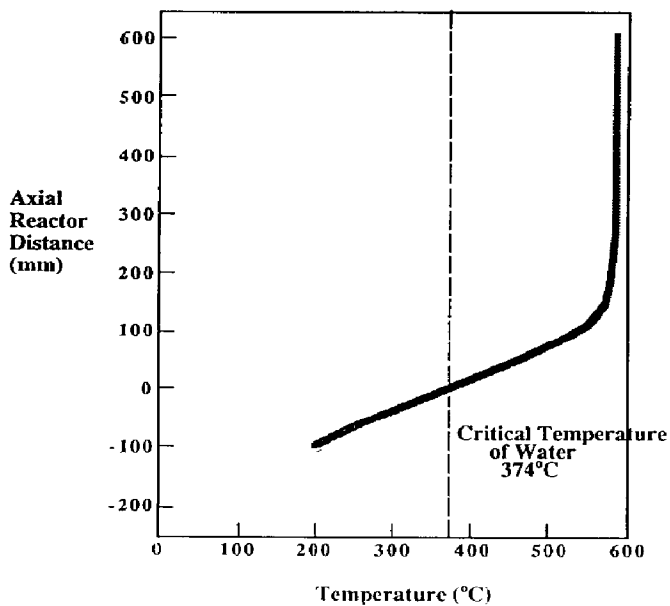


Fig. 3. Wall temperature gradient in pilot plant reactor.

the single reaction vessel. To illustrate this point, the steady-state pilot plant reactor wall temperature has been plotted versus axial distance in Fig. 3. Zero distance has been set at the critical temperature of water, 374 °C; positive distances reflect higher elevations where the temperature exceeds 374 °C; negative distances reflect lower elevations with lower temperatures. The plot shows that the transition from supercritical reaction temperature to subcritical temperatures is achieved over a relatively short distance of about 200 mm. There is a corresponding fluid density gradient which varies by a factor of about 10 over this same region. These variations in height within the reactor allow the principal process objectives of oxidation, and salt separation and re-dissolution to be achieved in a single vessel. They also, however, introduce variations in materials corrosion rates and influence the mechanical design of the vessel, as will be indicated later.

Engineering design issues

Any new process must confront the critical issues of scale-up and process integration. Due to the corrosive nature of the environment in the SCWO process and the relatively high pressure, identification of satisfactory materials of construction and their integration into a mechanically sound system becomes of paramount importance in the design. A detailed assessment of the technology and experience gained in the laboratory and pilot plant identified five key issues requiring concerted and focused engineering development.

- Process design and scale-up of the oxidation reactor.
- Control of (sticky) precipitating salts.
- Materials of construction for the reactor and downstream equipment.
- Mechanical design of the reactor and other high-pressure equipment.
- Integration of the process into a safe, environmentally acceptable system. (This had to account for limitations and constraints imposed by materials and mechanical design as well as normal process concerns.)

Since many aspects of these design issues are inter-related, a multidisciplinary (MODAR and ABB Lummus Crest) development team was assembled to work in these areas in parallel. The team was comprised of technical experts in SCWO chemistry and kinetics, process design, reactor simulation, metallurgy, mechanical vessel design, rotating machinery, process control, environmental engineering, and safety/hazard identification and analysis. This multidisciplinary approach has been effective in arriving at optimized solutions within a reasonable time for development. Each of the key development issues noted above is discussed in some detail in the following sections.

Reactor process design

The oxidation reactor must achieve several results: Organic waste feed and oxidant must be mixed and brought to the reaction initiation temperature; the

organic compounds must be oxidized to the required degree; the mineral acids formed during reaction must be neutralized by caustic; and the precipitating salts must be transferred into the (cold) bottom brine solution. The first two results are paramount in meeting the primary objective of the process. These aspects of the design were therefore analyzed and evaluated in detail by using a computational fluid dynamics simulation of the reactor based on the "PHOENICS" software available from CHAM of North America, Inc. This simulation solves the basic differential equations for the conservation of momentum, heat and mass, and thereby provides a basis for predicting reactor output performance for a given set of input conditions (feed flow rates, reactor geometry, nozzle dimensions, and fluid physical properties).

There is reason to believe that large organic molecules break down at reaction conditions, and that the rate of oxidation is controlled by the oxidation of smaller, partially oxygenated compounds. A (global) rate equation for the oxidation of ethanol was therefore used as the model kinetics in the chemical source term of the conservation equations. The rate equation was developed at relatively dilute ethanol concentrations in a medium of supercritical water at the Massachusetts Institute of Technology [5] assuming a first order reaction with respect to ethanol and zero order with respect to oxygen. For simulation purposes, the boundary of (cold) brine solution near the bottom of the reactor was treated as an isothermal plane allowing heat transfer, but no mass transfer. Radiation effects, in addition, were considered.

The simulation served as an effective tool to investigate reactor geometry, nozzle design, mixing of organic waste and oxidant, effect of feed preheat, fluid velocity field (including fluid flow reversal characteristics), rate-controlling mechanism (reaction kinetics versus diffusion), sensitivity of the extent of oxidation to temperature and flow rate variations, and scale-up in general. The model geometry used for this work together with the (variable) critical dimensions are shown in Fig. 4.

Representative results from the simulation of a 500 mm (internal) diameter reactor are shown in Fig. 5. The velocity vector field shows the expanding reaction jet as it discharges from the coaxial nozzle; a gradual dissipation of downward velocity is shown as the fluid traverses its path down the reactor, with upward flow indicated in the vicinity of the reactor wall. The temperature isotherm plot indicates that nearly full final reaction temperature is reached across the full reactor cross-section at a vertical distance slightly more than half of the distance from (feed) nozzle tip to bottom ("isothermal" plane); this particular simulation used aqueous/ethanol feed preheated to 265 °C. (The observed cooling effect near the reactor wall is due to heat loss to a cold water film maintained on the wall, described later in this paper and simulated here as a cold 315 °C isothermal wall.) Conversion contours show that, as expected, the conversion at the reactor (vertical) centerline is always the lowest conversion at a given horizontal plane; However, in this case the desired 99.99% con-

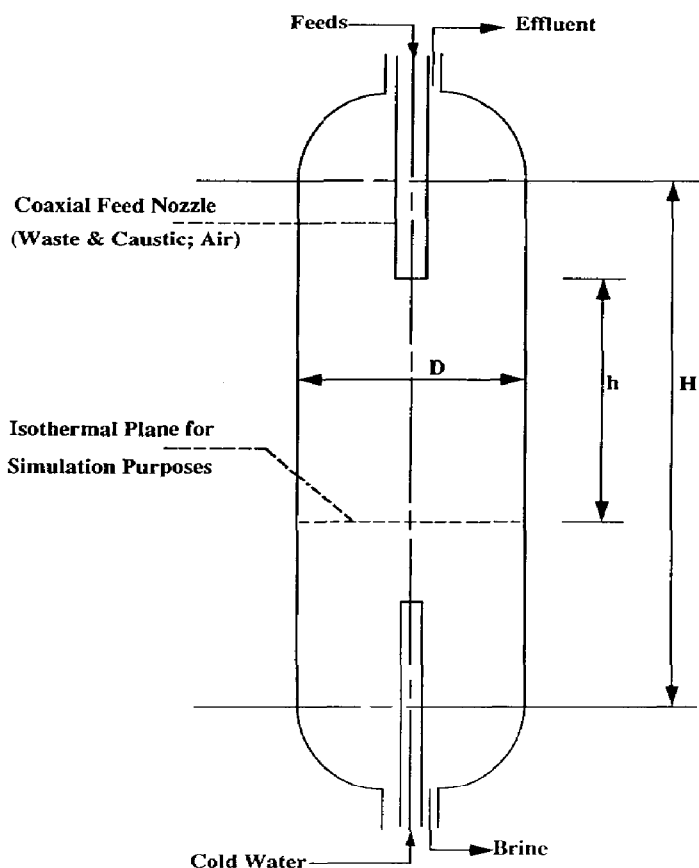


Fig. 4. Reactor model geometry.

version is achieved at the centerline at approximately 80% of the vertical distance from nozzle to reactor bottom. The simulation calculations indicated that "short-circuiting" of feed to the effluent stream in the countercurrent flow region near the top of the reactor is not significant.

Several important findings have resulted from the simulation studies:

- Reaction kinetics rather than turbulent diffusion controls the initial conversion rate in the reaction jet. Once sufficiently high fluid temperatures are achieved and the jet velocity field is largely dissipated, turbulent diffusion becomes rate controlling.
- A coaxial nozzle is satisfactory for achieving adequate dispersion and mixing of aqueous waste and oxidant.
- The simulation provides a rational basis for scale-up and for helping to establish reactor diameter, reaction jet height, and heat losses.

Sensitivity calculations using alternate reaction kinetics and varying feed rates, reaction temperature, etc., coupled with experimental results achieved

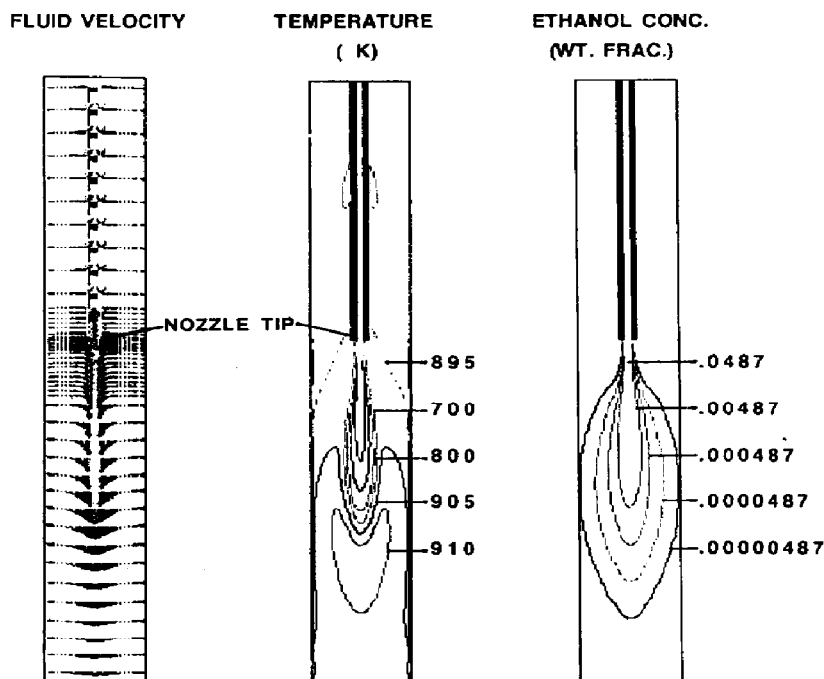


Fig. 5. Typical simulation results for fluid velocity, temperature, and ethanol concentration, respectively.

in the laboratory and pilot plant reactors, form the basis for establishing final reactor and feed nozzle dimensions in scaled-up plants.

To supplement the simulations, it is noted that field tests with the pilot plant reactor [3] have demonstrated 99.996% destruction efficiency based on organic carbon using the feed nozzle/cold reactor bottom configuration discussed above. For these same tests, ammonia destruction was greater than 99.71%.

Precipitation control

Control of salts within reactor

Qualitative characterization of the behavior of precipitated salts is possible for many waste feeds based on experience obtained in the laboratory and pilot plant. This characterization depends on the composition of the salt mix (the most commonly occurring constituents being some form of NaCl , Na_2SO_4 and Na_2CO_3), but also to some degree on temperature and supercritical fluid composition. In most cases, freshly precipitated salts are sticky and will tend to adhere to surfaces on which they impinge.

Fundamental salt formation studies with NaCl , Na_2SO_4 and mixed $\text{NaCl}/\text{Na}_2\text{SO}_4$ systems are underway at the Massachusetts Institute of Technology [6,7] using an optically accessible cell to examine phase behavior and solids nucleation in salt-water systems above the critical point of water. These ex-

periments will help to identify mechanisms of salt growth and to estimate the particle size of the solids formed. In the future, this type of information will be beneficial in further characterizing precipitating salts and in guiding the design of the reactor.

Most of the precipitating salts in an industrial reactor will be thrust into the cooled brine solution in the bottom zone of the reactor. However, due to fluid velocity components directed radially outward, some salt particles are expected to impinge and stick to a portion of the reactor wall unless provisions are made to avoid this. Several concepts for controlling salts accumulation on the reactor walls have been developed. One system is based on using a falling film of cold (approximately 300°C) water or dilute salt solution covering a critical height of the reactor where salt build-up is anticipated. It is designed to adhere closely to the wall, and to deflect or absorb and dissolve salts impinging the reactor wall, thereby minimizing the build-up of solid accretions.

Location of the water wall and the rate of heat transfer from the hot, center reaction zone to the curtain wall have been assessed with the aid of the reactor simulation procedure previously described. The temperature profiles shown in Fig. 5 include heat loss estimates to the water wall.

Control of entrained salts

Most of the precipitating salts report to the (reactor bottom) brine discharge stream, and leave the reactor as dissolved salts. However, a small fraction of the salts are elutriated with the overhead effluent stream containing most of the discharge H₂O, CO₂ residual O₂ and N₂. This stream also contains small amounts of salts dissolved in the supercritical fluid. The loading of particulates in the overhead stream depends on solids particle size and density and on the upward superficial fluid velocity (and hence, reactor diameter). In order to minimize salt accumulation in the downstream piping and equipment, the overhead stream is rapidly quenched by recycle quench water to a temperature below the salt inversion temperature. The preferred quench temperature is a matter of design for a specific application, but is generally in the range of 300 to 350°C.

This cooling step is operated as a condensing quench (with H₂O partially condensed from the reactor overhead) and is designed to re-dissolve any entrained salt fines, thus alleviating the need for any high-temperature solids/fluid separation equipment.

Materials of construction

The materials selection program had to address the reactor environment as well as auxiliary process areas such as the brine pressure let-down system and the water wall recirculation loop. The specific chemical environments in the process depend partly on the nature of the waste feeds treated. The approach taken in the development program was, therefore, to establish corrosion data

for the most severe chemical conditions. This is the treatment of chlorine and sulfur containing materials with *in situ* caustic neutralization and the presence of precipitating salts. Process stream compositions downstream of the reactor were determined from laboratory and pilot experience, as well as from process heat and material balance calculations.

An important observation from the experimental work was that due to steady state temperature and concentration gradients within the reactor, it would be difficult to simulate the full range of reactor conditions in a static autoclave system. Consequently, it was determined that realistic reactor corrosion data could only be obtained in a dynamic reactor system. Several prolonged experimental campaigns were therefore conducted in the continuous-flow bench scale reactor with the exposure of long narrow strip specimens which covered the entire height of the reactors.

Alloys tested concentrated on high nickel, high chromium alloys and included Inconel 625, alloy 556, Hastelloy C22, C276, and alloys MC-3, G-30, Allcorr and several grades of titanium (for low temperature only). Specimens were prepared in various forms: As received, stress relieved, and assemblies to simulate the tendency for crevice corrosion. Exposed specimens were first visually examined under low magnification, and were then sectioned at strategic locations for the preparation of microsections; photomicrographs were prepared under higher magnification for characterization of corrosive attack. Exposed metallic strips from one campaign, prior to any sectioning, are shown in Fig. 6. These specimens show an accumulation of sodium salts in the mid-region of the photograph due to the strips penetrating the reaction jet where salts were being precipitated. The results from this program, in general, showed considerably higher corrosion rates than is typically considered acceptable in the design of conventional chemical process plants.

Several similar experimental campaigns were also conducted for 12 different ceramic and mortar materials. Here, specimens (Fig. 7) were assembled in a "sandwich" arrangement between alloy strips for vertical suspension in the bench-scale reactor. These materials were tested in support of a "cold wall vessel" design in which a ceramic/refractory system is used as a barrier between the harsh reactor fluid and the vessel wall. Exposed specimens were evaluated to determine whether there had been surface deterioration and penetration into the samples. Results from one campaign are shown in the photograph of Fig. 7 where partial dissolution of two of the materials is apparent. This experimental program led to the identification of at least one ceramic material which performed well in all zones (hot, transition, and cold) of the reactor, without evidence of surface penetration.

Three additional (static) autoclave test programs were carried out with chemical solutions representing process streams outside of the reactor. These were conducted for a minimum exposure of 500 hours with frequent replenishment of solutions; this replenishment was done to minimize contact with par-

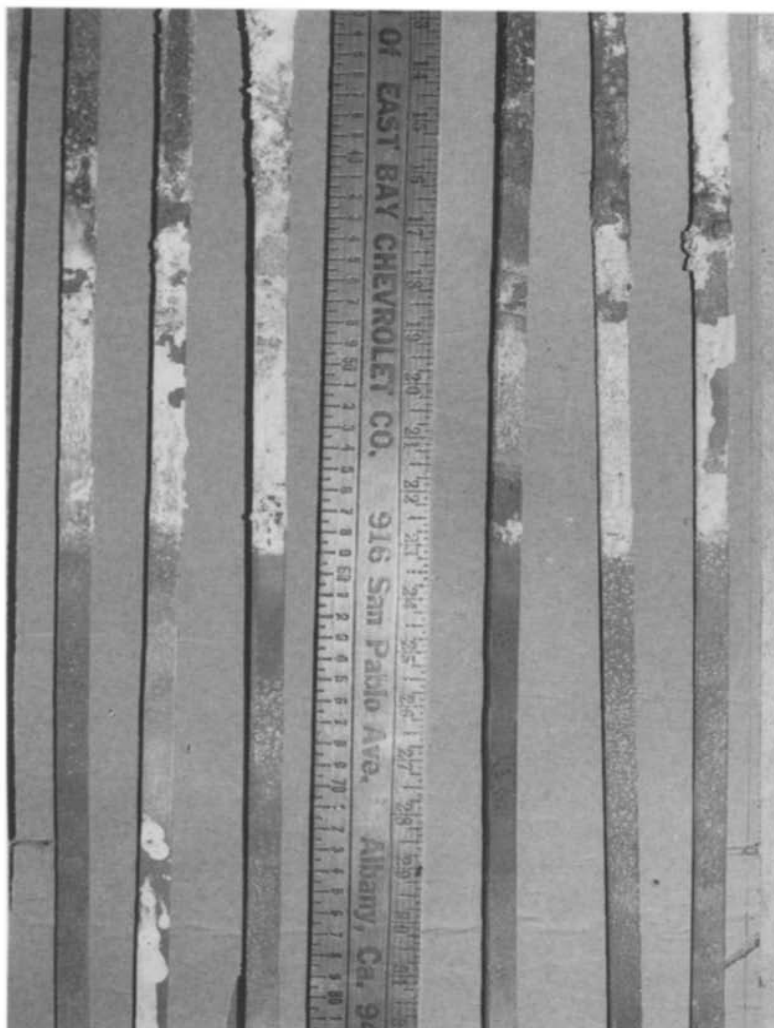


Fig. 6. Example of alloy test specimens exposed in bench-scale reactor.

tially depleted solutions or possible solution corrosion products. Alloys similar to those discussed above were used, but due to the lower temperatures, a number of grades of titanium were emphasized. These tests confirmed the suitability of titanium for these process areas.

In sum, the materials testing program has provided a suitable basis for materials selection in the reactor and auxiliary process areas.

Mechanical design considerations for oxidation reactor

The oxidation of organic materials in supercritical water under the stated operating pressure and temperature presents a significant challenge to the mechanical containment of the process. This challenge is the result of the severely corrosive nature of the reaction fluid coupled with temperatures which are well

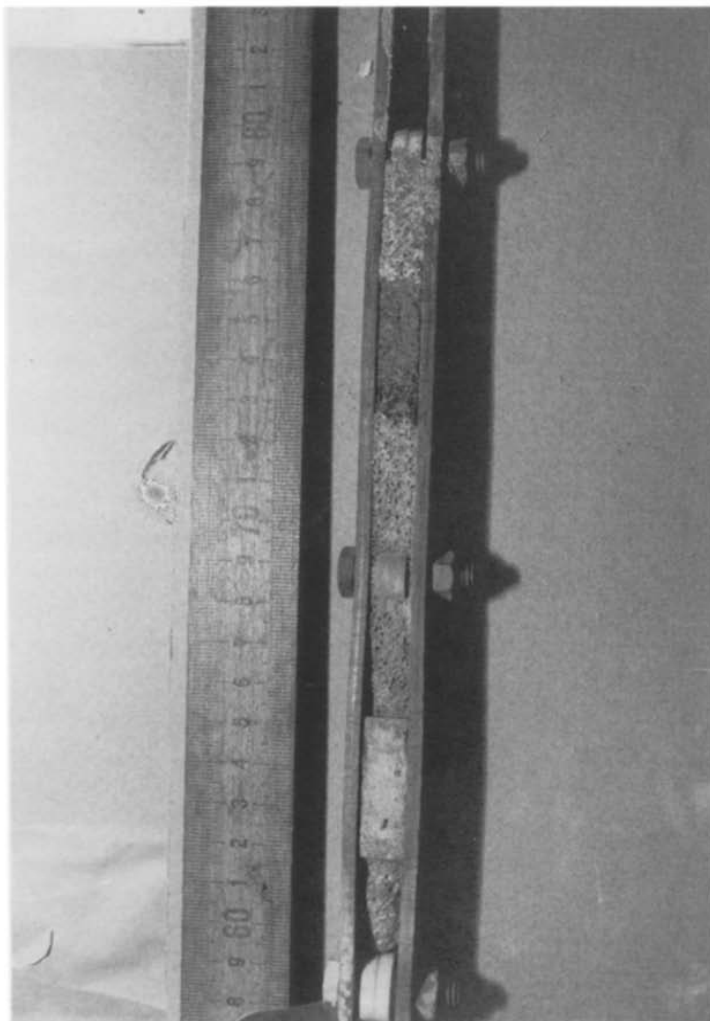


Fig. 7. Example of ceramic test specimens exposed in bench-scale reactor.

into the creep range of suitable structural materials of construction. In addition, the elevated pressures of operation require a high integrity containment vessel which provides suitable safety for the protection of life and property as well as a reasonable operating life.

The methodology employed in the development of the SCWO reactor is typical of that which has been used in the development of other reactor concepts. The first attempt was to provide the simplest design mechanically which satisfies the process operating requirements. This would be an externally insulated (hot wall) design in which the process fluids are in direct contact with the pressure containment. Although this concept is conventional in many other process systems and meets SCWO process requirements in a simple design, its

applicability in this case is severely limited by a number of practical mechanical constraints as outlined below.

The SCWO reaction environment is extremely corrosive to all structural materials of construction. This leads the designer to incorporate an overlay of a non-structural material, i.e., one not suitable for containment of the pressure, but which provides corrosion protection of the structural material. However, the only materials determined sufficiently reliable for this corrosion protection are the noble metals. Although such a concept is possible, the application technique would be difficult and the cost of the overlay material as well as its application would be very high. In addition, the operation of a hot wall reactor would result in the structural material being operated well within the creep range. This is relatively common practice within industry, and safety is typically maintained by designing the equipment for a reduced allowable stress. It is not typical, however, to expose equipment in the creep range to large steady-state thermal gradients (reactor top to bottom), as well as potential thermal shocks that may be incurred during upset conditions. These considerations coupled with the very high operating pressure would result in an impractically thick reactor wall design whose safety may be progressively compromised over time.

An alternate approach to alleviating the creep/fatigue concern would be to design the reactor using a structural material which is less susceptible to creep effects. These materials, however, typically either provide relatively low strengths or as in the case of Inconel 625, are subject to loss of ductility (i.e., embrittlement) after long term exposure within the SCWO operating temperature range. Again, this would result in an impractical reactor thickness with compromised safety over time.

ABB Lummus Crest, Inc. has therefore developed two proprietary reactor concepts based on using cold-wall pressure containment designs. Both concepts separate the reaction fluid from the pressure containment vessel by suitable material(s), as established in the materials test program. Details of these designs are proprietary, pending patent filing.

Process integration

Various configurations have been examined for integrating the concepts presented in this paper into a coherent process scheme. The most common arrangements are discussed below, using the block flow diagram in Fig. 8 as a guide.

Aqueous waste containing, for example, hazardous organic materials, spent solvents, or waste sludge, is pressurized and fed into the reactor along with compressed air or oxygen. If necessary, caustic soda is injected into the feed stream to neutralize acids generated during the oxidation reactions. If desired, the feed stream may be pre-heated by cross-exchange with the effluent stream; the viability of this heat exchange step and the specific temperature to which

the feed may be preheated will depend on the stability of the organic constituents and their resistance to polymerization, decomposition, etc., and hence tendency to foul heat exchange surfaces.

The feeds are injected into the reaction vessel by means of a coaxial nozzle. Feed materials are subsequently mixed, heated and reacted in the resulting fluid jet. Inorganic salts precipitate and in the main are thrust toward the bottom of the reactor where the salts are cooled, re-dissolved and extracted in the form of a brine solution. Gaseous reaction products, primarily carbon dioxide, nitrogen and supercritical water, leave through the top of the reactor. A small amount of dissolved and entrained salts is also discharged with the gaseous effluent.

Reactor effluent is quenched by direct contact with a recycle water stream, thereby dissolving the small amount of salt in this stream, and the resulting gaseous and liquid streams are separated by gravity in a quench separator vessel. The gaseous stream undergoes pressure let-down and, if necessary, is passed through a fixed bed catalytic oxidizer (not shown in Fig. 8) to oxidize residual carbon monoxide, before being discharged to the atmosphere.

Quench separator liquid is cooled and recycled to the quench step. A portion of this stream (depicted as the net liquid make in Fig. 8) can be used to pre-heat the feed. Heat can also be recovered from the recycle stream in the form of low pressure steam. The optimum heat balance arrangement for a given

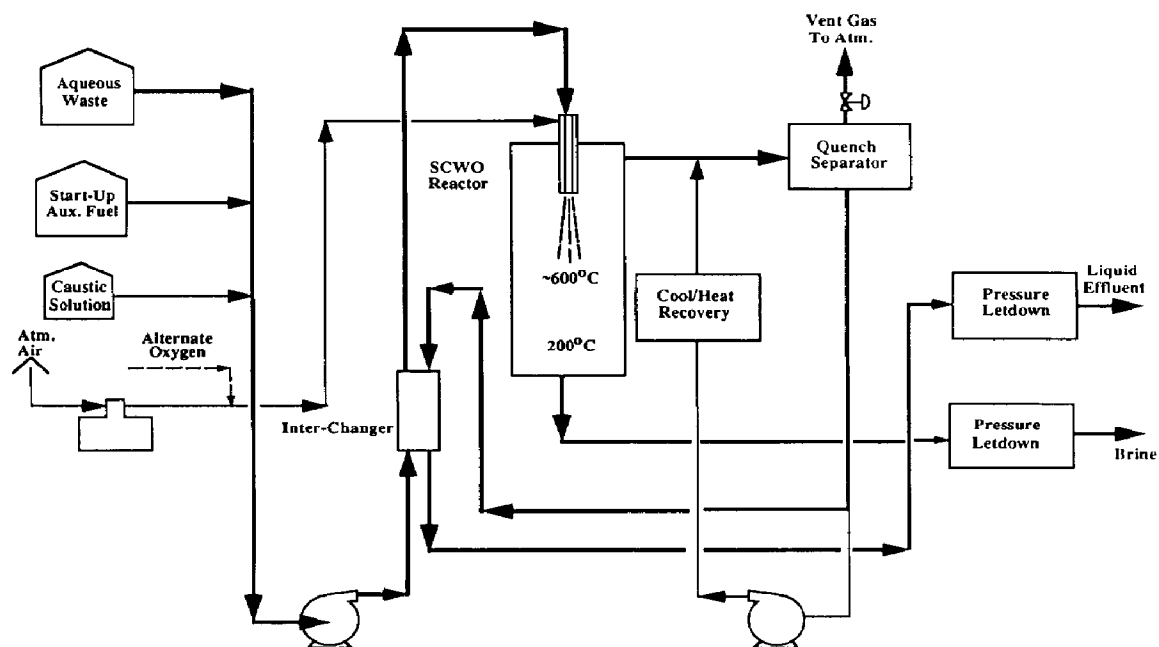


Fig. 8. Block diagram showing process configuration.

application will depend on the nature of the waste feed, plant capacity and the benefits of heat recovery, and will generally be based on process economics.

The net liquid effluent, as well as the brine solution discharged from the reactor bottom, undergo pressure let-down prior to discharge. In situations where salt discharge in the liquid stream can be accommodated, it is possible to combine the pressure let-down systems for the two liquid streams. In cases where the produced salt must be disposed to a contained facility, evaporation of the brine stream to produce a salt cake may be desired; here, recovered process heat can be utilized to supply the necessary energy.

In situations where a waste stream containing dilute concentrations of organic materials must be treated, it is advantageous to consider simultaneously the destruction of a (high heating value) waste solvent stream, thereby providing a composite waste of the desired (chemical) heating value. For reference purposes, autogenous operation of the process is possible without feed preheat when the (chemical) heat content of the composite aqueous waste stream is about 4.5 to 5.0 GJ/m³ of feed. The required heat content is progressively decreased as the extent of preheat is increased. Another factor entering the heat balance arrangement for a specific application is the amount of recoverable heat, which without feed preheat, is approximately 3 GJ/m³ of waste feed when producing low pressure process steam.

Most of the design effort to date has focused on the use of air as oxidant. However, ABB Lummus Crest has recently entered into a cooperation agreement with L'Air Liquid (LAL) of Paris for the commercial development of the process. This cooperation will include LAL's participation in the further evaluation of the benefits of an oxygen-based plant.

Status of technology

Essential elements of a basic engineering design for a generic commercial plant have been developed. These include: Process flow diagram, heat and material balances, process equipment data sheets, preliminary process and instrumentation diagrams, preliminary safety review, process control concepts, and plot plan. The work described in this paper has also led to a rational basis for process scale-up, selection of materials of construction and identification of two viable mechanical concepts for the reactor. These efforts have progressed in sufficient detail to proceed with the next step of designing, constructing, and assessing operation in a demonstration plant.

Process scale-up and mechanical design criteria, and technical risk considerations suggest that the demonstration plant should have a capacity to treat a composite aqueous waste stream in the range of 10 to 20 m³ per day in the lower range, and 100 to 150 m³/day in the upper range. ABB Lummus Crest is actively pursuing opportunities for such a facility at this time.

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