

# Computer Simulation Helps Assure Success of First Indirect-Radiant Gas-Fired Annealing of Nuclear Reactor

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The heat exchanger prior to its installation inside the reactor vessel

The first ever indirect, gas-fired, radiantly heated annealing of a nuclear reactor was a major success, thanks partly to computer simulation that validated the process in advance. After years of neutron bombardment, nuclear reactor pressure vessels become brittle. Annealing restores the ductility and fracture toughness of the weld metal, adding many years of operating life to the reactor vessel. The problem is that annealing requires heating the entire vessel to a temperature of approximately 850°F for a week.

The embrittlement problem forced Yankee Atomic

Electric Co. to decommission its Rowe power plant outside Boston in 1992 eight years before its license was due to expire.

The annealing approach pioneered by Westinghouse Electric Corporation and Cooperheat Inc. involves blowing in superheated air from gas fired burners into a heat exchanger that in turn heats the reactor vessel. This approach was validated, prior to a successful six million dollar demonstration project, by building a functional scale mockup and by simulating heat transfer and air flow using computational fluid dynamics (CFD) software.

The nuclear power industry is looking at thermal annealing as a remedy for neutron-induced embrittlement of reactor pressure welds in nuclear reactors. The pressure vessel contains the fuel and control mechanism for the nuclear reactor and is located within the containment building. Metallurgical experiments have shown that annealing the vessel will restore it to near its original metallurgical properties. This requires disassembling the internal components of the reactor (a standard operation during refueling) and providing a means for in-situ heating of the 35 foot tall, 15 foot diameter vessel. Because they specialize in heat treating applications, Cooperheat engineers were asked to take a look at the problem.

The size of the reactor vessel alone is not a major

obstacle; Cooperheat regularly heat treats many larger pressure vessels for the petroleum industry.

The difficulty of the task relates more to the fact that the inside of the reactor is contaminated with radiological materials that cannot be released to the environment. This eliminates the most common method used to anneal large pressure vessels, which is circulating superheated air from gas burners inside the vessel and insulating the outside of the vessel to minimize heat loss. The problem is that the hot combustion gases would pick up radioactive dust and other contaminants inside the vessel and spread them into the atmosphere.

Several nuclear reactors in Russia have been annealed using radiant electric heat. Cooperheat engineers decided not to use this approach for several technical and economic reasons. Ironically, despite the fact that the pressure vessel was located within an electric generating facility, obtaining power for the heaters would have been very costly. Another problem with this approach is that a failed electric heater element would have been virtually impossible to repair or replace inside the reactor. The use of redundant electric heaters would have nearly doubled the cost and the weight of the furnace.

For these reasons, Cooperheat engineers decided to pioneer an alternate approach for annealing reactors. This method uses gas-fired burners to superheat air and blow it through sealed ducts in existing openings in the containment building, such as the equipment hatch, into the heat exchanger inside the reactor vessel. The superheated air is then discharged outside of containment through another duct to the atmosphere. Since the air never comes into contact with any contaminated surfaces, it does not become contaminated. The gas-fired heaters are located outside the containment building so they can be easily replaced in case of failure.

This approach clearly had the potential to eliminate many of the problems with electric heating. But it also raised several potential difficulties of its own. The main one was insuring that the heat exchanger would be able to maintain temperature uniformity throughout the entire reactor vessel annealing zone. The problem with not achieving adequate

temperature uniformity is that it can create excessive thermal stresses. Much analysis was performed to verify that the reactor vessel would not be overstressed. Cooperheat built and tested a scale model of the heat exchanger and reactor vessel very early in the project to experimentally estimate heat transfer coefficients. Cooperheat engineers also elected to use the CFD method to simulate flow distribution and heat transfer within the heat exchanger to confirm the experimental results.

A CFD analysis provides fluid velocity, pressure and temperature values throughout the solution domain for problems with complex geometries and boundary conditions. As part of the analysis, a researcher may change the geometry of the system or the boundary conditions such as inlet velocity, flow rate, etc. and view the effect on fluid flow patterns or concentration distributions. CFD also can provide detailed parametric studies that can significantly reduce the amount of experimentation necessary to develop prototype equipment and thus reduce design cycle times and costs. Cooperheat engineers selected FIDAP CFD software from Fluent Inc., Lebanon, New Hampshire, because FIDAP uses the finite element method which is ideal for generating the complex and irregular geometries which were involved in the proposed heat exchanger design. The flexibility of the mesh generation tool provided with this software package makes it possible to handle very odd shapes. Another advantage of this program is that it was offered at a very reasonable price for the company's existing computer system.

Cooperheat engineers first developed an initial design for the heat exchanger. Fluent consultants modeled the flow within the heat exchanger using the assumption that flow within the heat exchanger would be uniform. The initial design verified the experimental heat transfer coefficients, based on the assumptions that were made. Next, the consultants modeled the distribution system which provided hot gases to the heat exchanger to make sure that it actually met the uniform assumptions of the first analysis. The initial design had assumed that a single injection point would provide uniform circulation within the heat exchanger. The analysis showed that, with only a single injection point, the hot gases

impinged upon the wall of the heat exchanger and created a recirculation zone. This could have caused a cold spot that would have prevented the heat exchanger from uniformly heating the reactor vessel.

Consultants changed the model several times and re-ran the analysis to evaluate the results. Cooperheat engineers finally settled on the use of four injection points which provided the uniform flow required to achieve uniform heat transfer.

With the experimental results confirmed, Cooperheat engineers were able to proceed with confidence that the new process would work as expected. The first opportunity to use the new process came at a demonstration at Public Service of Indiana's never-completed Marble Hill plant near Paynesville, Indiana. The annealing demonstration at Marble Hill was carried out with the combined resources of the Department of Energy's Sandia Laboratories and an industry consortium including the American Society of Mechanical Engineers, the Electric Power Research Institute, Consumers Power Company, Japan's Central Research Institute of the Electric Power Industry, Westinghouse and Cooperheat.

The reactor vessel was heated for seven days and 10 hours, as the heat exchanger reached a temperature of about 1,100°F. The reactor pressure vessel was brought to its peak temperature at a rate of about 20°F per hour and cooled down at the same rate. Each of the five gas burners produced two to three million BTUs of heat per hour. During the annealing process, the pressure vessel and surrounding components were monitored by over 500 thermocouples, strain gauges and displacement gauges.

An important concern during the testing was showing that the vessel maintains a fairly even temperature distribution during annealing in order to avoid the stresses associated with thermal variations. Another concern was avoiding damage from the fact that the vessel expands as it is heated, but the piping and other connections surrounding the vessel do not experience the same expansion.

The test was a complete success. All measurements showed that the vessel maintained an even temperature during the annealing process.

Preliminary analytical results verify that the metal throughout the vessel walls, welds and attached piping expanded and contracted without damage exactly as predicted.

The Marble Hill test proved that aging reactor vessels can be rejuvenated and their operating life substantially extended, permitting old reactors to continue operations for many years.

Steve Trich, General Manager of Westinghouse's Nuclear Services Division, stated: "The technology and overall annealing process demonstrated at Marble Hill went well beyond our expectations. This successful demonstration overturns a major hurdle faced by utilities with aging reactor vessels. Utility executives can confidently plan to extend the life of their reactors knowing that vessel embrittlement need not be an impediment."