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CFD and Safety Factors

Computer modeling of complex processes needs old-fashioned experiments to stay in touch with reality.

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Computational fluid dynamics is recognized as a powerful engineering tool. That is, CFD has advanced over the years to the point where it can now give us deep insight into the analysis of very complex processes. There is a danger, though, that an engineer can place too much confidence in a simulation. If a user is not careful, it is easy to believe that if you plug in the numbers, the answer comes out, and you are done. This assumption can lead to significant errors.

As we discovered in the course of a study on behalf of the Department of Energy's Savannah River Site in South Carolina, CFD models fail to capture some of the large variations inherent in complex processes. These variations, or scatter, in experimental data emerge from physical tests and are inadequately captured or expressed by calculated mean values for a process. This anomaly between experiment and theory can lead to serious errors in engineering analysis and design unless a correction factor, or safety factor, is experimentally validated. For this study, blending times for the mixing of salt solutions in large storage tanks were the process of concern under investigation.

Radioactive liquid waste is stored at the Savannah River Site in 49 underground storage tanks that vary in capacity from 850,000 to 1.3 million gallons. There are several waste forms in the tanks: settled solids, referred to as sludge; precipitated salts, known as saltcake; and salt solutions, called supernates. Sludge is mixed with glass, and salts will be removed from solution and mixed with grout to form saltstone for disposal. Excess water is further decontaminated to meet regulatory requirements before release to the environment. The waste-handling processes related to these waste forms are overseen and managed by a site contractor, Savannah River Remediation LLC.

This study focused on the blending processes needed to mix salt solutions to ensure homogeneity within waste tanks, where homogeneity is required to control radioactivity levels during subsequent processing. Two of the requirements for this task were to determine the minimum number of submerged, centrifugal pumps required to blend the salt mixtures in a full-scale tank in half a day or less, and to recommend reasonable blending times to achieve nearly homogeneous salt mixtures. To these ends, Savannah River Remediation enlisted the Savannah River National Laboratory to study blending processes. Prior to this research, two pumps were to be purchased for blending salt mixtures in each of two tanks, but this research showed that a single pump is adequate in each of the two tanks.

The principle for blending is the same for all blender-pump designs: the business end of a centrifugal pump will be submerged in the salt solutions in the tank. The pump's suction inlet is located just below two opposing nozzles and liquid is drawn up into the impeller and then accelerated and discharged through the opposing nozzles into the tank to blend the tank contents.

Savannah River National Laboratory was asked to recommend the nozzle flow rate and the nozzle diameter for a pump, along with the expected blending times for the selected pump design. A full-scale, low-flow pump with a total discharge flow rate of 500 to 800 gpm was recommended with two opposing 2.27-inch diameter nozzles. To make this recommendation, both experimental and CFD modeling were performed. More than 40 engineers, mathematicians, and technicians significantly contributed to the fast-paced research.

Laboratory researchers performed experimental blending tests and velocity measurements in an eight-foot diameter, 993-gallon nonradioactive pilot-scale tank. To do so, the lab performed a total of 126 pilot-scale tests, 260 material property tests, and created 39 CFD models over 15 months. All the pilot-scale test equipment was fabricated and initial testing started within 16 work days.

Some full-scale test results and CFD models were available from previous site research on a high flow (10,500 gpm) pump. In particular, experimentally determined velocity measurements were available from testing in a nonradioactive 85-foot diameter tank that held 340,000 gallons.

Parallel to running the experiments, SRNL performed comparable CFD models for both the pilot-scale and full-scale tanks, using the Fluent CFD code from Ansys of Canonsburg, Pa. In early project discussions, the researchers agreed that autonomy of CFD research and experimental research was essential to prevent biased CFD modeling results. Consequently different engineering organizations within the laboratory independently performed the CFD modeling and experimental testing. CFD modelers verified and validated the Fluent CFD code using the lab's procedures.

To bring all of this research together, the process variables investigated were the fluid velocities in the tanks and the times required to blend the fluids. As experiments were completed, experimental and CFD results were compared and analyzed.

Blending times were investigated for two different scenarios in the pilot-scale tank. For most of the blending tests, tracer quantities of chemicals were added to the tank. For a few of the tests, large quantities of fluid were added to the tank to evaluate the effects on blending times caused by bulk additions, rather than additions of tracer quantities.

Lab researchers found that, although CFD provided good estimates of an average blending time, experimental blending times varied significantly from the average. The issue of experimental uncertainty is inherent in CFD modeling as well as in many empirical equations used for modeling and design methods. For example, fatigue limits and fatigue lives are commonly used in piping and machine design; but experimental fatigue life data is typically plus or minus a factor of 10. Another example is the piping design requirements for the ASME, B31.3 <ital>Process Piping Design<endital>, where a design margin, or safety factor, of three is used with respect to the ultimate strength as one criterion to compensate for variations in material and structural properties.

For the research related to the Savannah River project, the experiments were performed to benchmark, or validate, CFD modeling techniques. The safety factors, or correction factors, were established through a statistical comparison of experimental results to CFD predictions.

A Savannah River Lab mathematician performed an independent statistical analysis of experimental and CFD results. The first variable to be considered involved velocity, for which there were data from new pilot-scale tests and records of testing in the full-scale tanks. The mathematician showed that experimental deviations from CFD results were 27 percent.

When it came to the blending time variable, the variation from CFD results was considerably larger for pilot-scale blending of tracer quantities. When variations in both the velocity and blending times were combined, the blending times varied from the CFD prediction by 74 percent to 164 percent, depending on the number of flow obstructions in the tank. That is, the obstructions increased the system complexity along with the blending times and the variations of those blending times with respect to CFD predictions. The obstructions in the tank consisted of vertical, serpentine cooling coils in some of the waste storage tanks.

In short, the correction factor for velocity is 1.27, and the correction factors for blending times vary between 1.74 and 2.64, where a CFD calculated blending time is multiplied by the correction factor to obtain a recommended blending time.

Blending times may also increase significantly when the blending process is changed. For example, when large bulk quantities of fluids were blended instead of blending tracer quantities into a large quantity of fluid, the blending performance was significantly different. Depending on how the fluids are added to the tank, the required blending time may decrease or may be forty, or more, times the CFD calculated blending time. Blending times for bulk additions to tanks require further research.

The laboratory completed the primary research goals and recommended a minimum flow rate and optimal nozzle diameter for a single, non-rotating pump, and the blending time for the pump. A technical validation was established for future CFD models, using experimentally derived correction factors, for blending of tracers in tanks. Recommendations were also provided to reduce the number of operating pumps required to effectively blend salt solutions to prepare them for further processing.

The need to buy fewer pumps reduced costs by a conservatively estimated $3.5 million. The pumps that have been procured for blending solutions in waste tanks cost on the order of $1.2 million each, and each pump has additional costs. To prevent the spread of radioactive contamination at the waste tanks, containment structures with ventilation are required to be constructed every time a pump is installed or removed from a tank. Additional costs are also incurred to dispose of radioactively contaminated pumps.

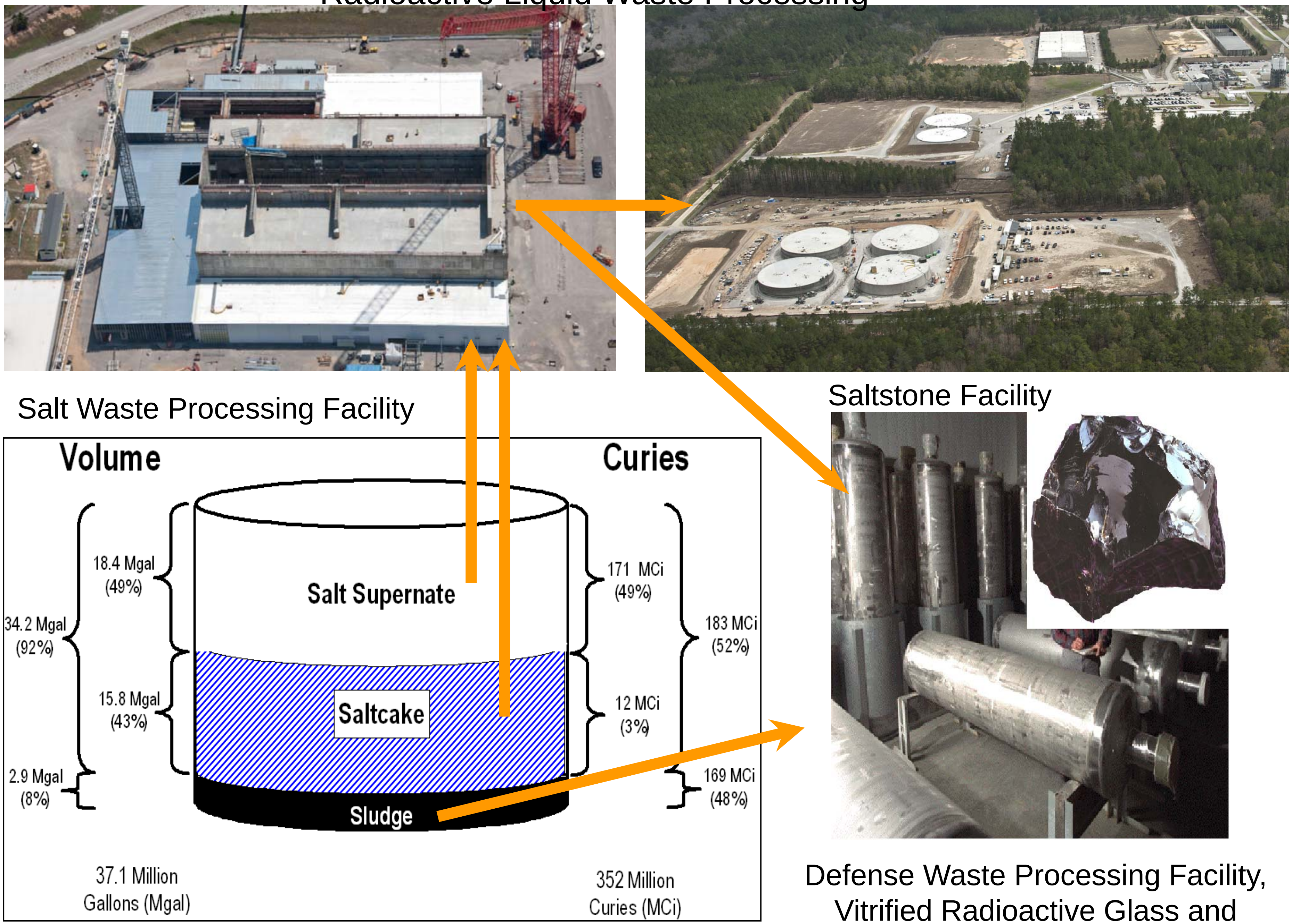
An additional result of the study is that it provided us a better understanding of how to use CFD models in general.

This research demonstrates the need for experimental validation of CFD models for complex processes, such as blending. The large scatter in experimental data shows that large errors can be obtained from CFD models in the absence of experimental correction factors. One example in this research showed that the average blending time was reasonably predicted by CFD, but the actual blending time could be more than two and a half times that value. This type of uncertainty may apply to other complex CFD applications.

Sidebar, use on lead spread:

A thread to all references which support this discussion is available through the ASME paper "Comparison of Experimental Results to CFD Models for Blending in a Tank Using Dual Opposing Nozzles," by R.A. Leishear, M.R. Poirier, M. D. Fowley, S.Y. Lee, and T.J. Steeper, IMECE 2011-62042, International Mechanical Engineering Congress and Exposition, ASME.

Radioactive Liquid Waste Processing



Salt Waste Processing Facility

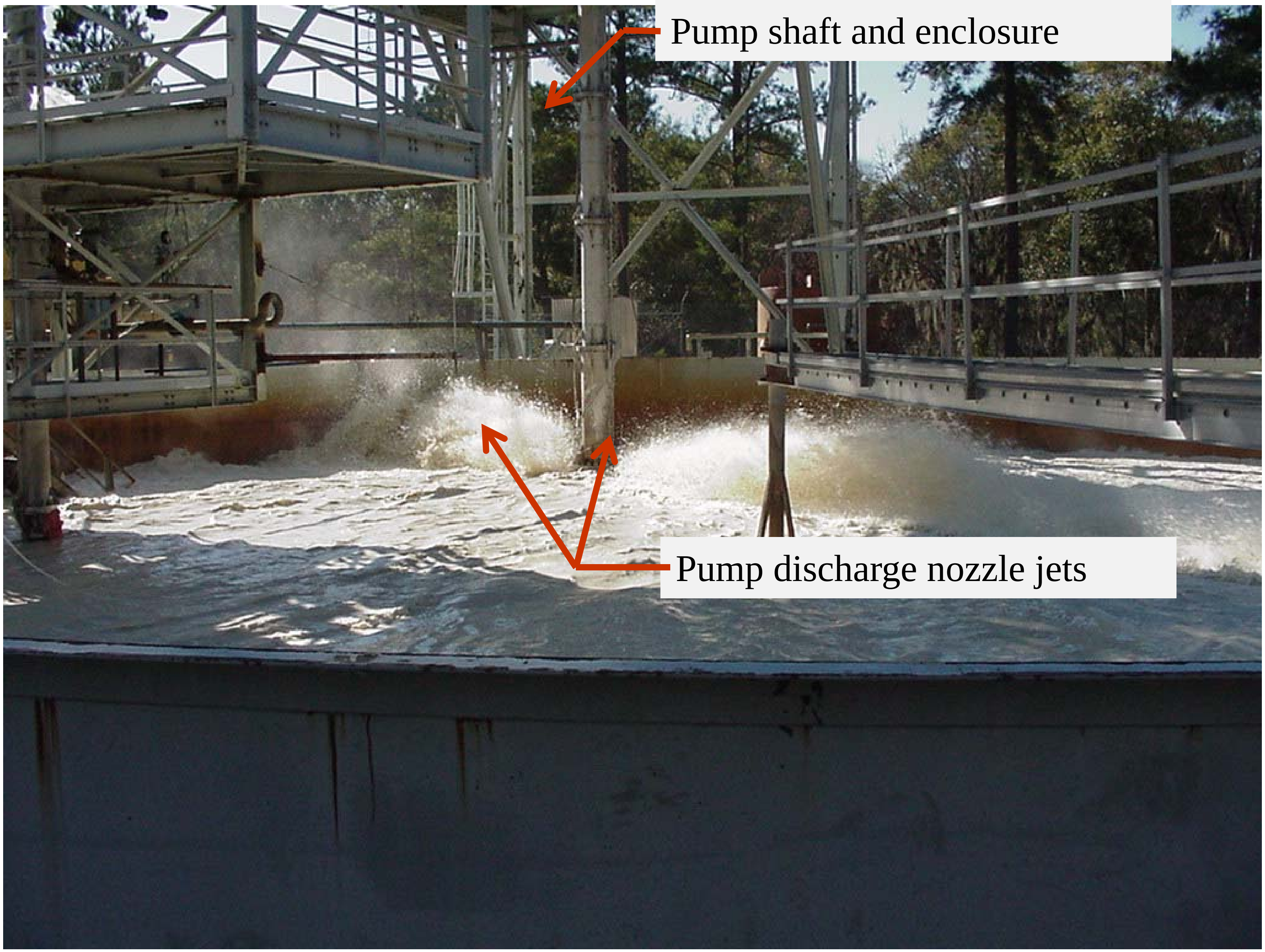
Saltstone Facility

Radioactive Liquid Waste Forms

Defense Waste Processing Facility,
Vitrified Radioactive Glass and
Storage Containers

Eight Foot Diameter Pilot Scale Model of a Waste Tank

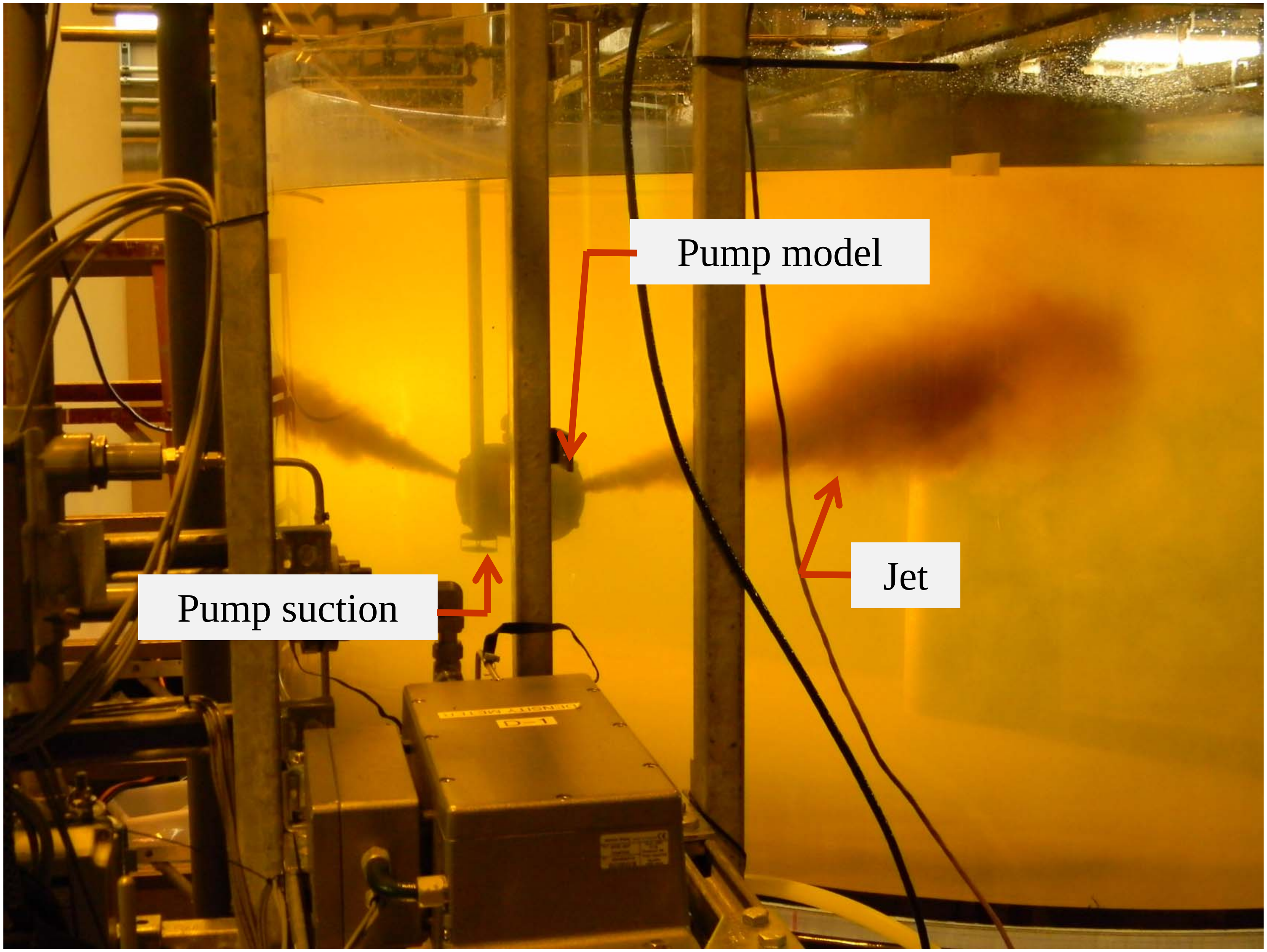
Full Scale Pump



Pump shaft and enclosure

Pump discharge nozzle jets

Pilot Scale Pump Model



CFD Model of Mixing in a Million Gallon Waste Storage Tank