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EXPERIMENTAL FACILITY AND VOID FRACTION CALIBRATION METHODS FOR IMPEDANCE PROBES

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ABSTRACT

An experimental facility was designed and constructed with aims of to calibrate a capacitance probe for gas-liquid flow void fraction measurements. The facility is composed of a metallic hack with a vertical 2,300 mm high glass tube with 38 mm ID with stagnant water and compressed air bubbling system simulating the gas phase (vapor). At the lower part, a mixing section with a porous media element releases the air bubbles into the water, and the compressed air flow is measured by two calibrated rotameters. At the upper part a stagnant water tank separates the liquid and gas. Two pressure taps are located near the lower and upper sides of the glass tube for pressure difference measurement. The pressure difference is used for low void fraction values (0-15%) calibration methods, as described in the work. Two electrically controlled quick closing valves are installed between the porous media element and the upward separation tank for high void fraction values measurement (15-50%) used to calibrate the capacitance probe. The experimental facility design, construction, capacitance probe calibration methods and results, as well as flow pattern visualization, are presented. Finally, the capacitance probe will be installed on a natural circulation circuit mounted at the Nuclear Engineering Center (CEN/IPEN/CNENP-SP) for measurement of the instantaneous bulk void. Instantaneous signals generated by the capacitance probe will allow the determination of natural circulation loop global energy balance.

1. INTRODUCTION

Natural circulation circuits (NCC) are important hydraulic systems of new generation of nuclear reactors designed for, in certain circumstances like startup, safe and accident shut off, having the function of secure cooling system, removing heat flux from reactor core and maintaining a safe reactor cooling capacity. As a recently implemented technology, NCC behavior under various operational conditions have been extensively studied by research groups worldwide to understand the main flow and heat flux transport mechanisms that occur during it operation. NCC operates governed by the interplay of inertia, buoyancy and friction forces, being important to the residual heat removing in case of primary circuit fail. They can operate as a cooling circuit for monophasic and biphasic flow dynamics. In monophasic mode, no phase change occur (no vapor formation) during heat transfer processes, but in biphasic mode the cooling fluid changes from liquid to gas (vapor formation and transport) during heat transfer process.

At biphasic operation mode, the two-phase heat transfer process and mixture flow must be well known concerning control, design, safety, and performance developments. It requires the knowledge of heat transfer coefficient and mixture (vapor and liquid) flow parameters, like mixture void fraction. As can be proved by predicting methods the heat transfer coefficient is dependent on mixture void fraction distribution and flow regime. So far oscillatory heat transfer problem, the flow boiling, is affected by the influence of flow direction on the heat transfer coefficient and mixture void fraction during fully developed nucleate boiling in the vertical channel (hot leg). Void fraction is no longer the main parameter to be determined for the best two-phase flow understanding [1-4] and, mainly, for determining transport equations.

The NCC of CEN/IPEN has operational behavior similar but in reduced scale conditions as it should operate in a real nuclear reactor, and the a void fraction sensor is a key to determine two-phase flow variables (mainly void fraction), flow patterns behind other parameters with minimum uncertainty, once many other variables are directly associated with void fraction.

1.2. Two-Phase Flow Sensors

Void fraction measuring techniques have been extensively studied in last decades in connection with determining the void fraction and characterizing the two-phase flow structure and regime. Two-phase are characterized as a largely fluctuating, requiring the use a specific instrumentation. Instrumentation development is the important for the multiphase flow modeling as well as for flow monitoring purposes. Many techniques for void fraction measurement have been developed, and their particular success depends on a specific application. The signal response is two-phase flow structure-dependent and can be designed to indicate void fraction values that are instantaneous or time-averaged, local or global.

The electrical impedance technique is one of the most promised techniques for void fraction measurement, whose working principle relies on the difference in electrical impedance of each fluid phase. Invasive to the flow or non-invasive sensor configurations have been investigated for local void fraction distribution and the phase interfacial area determination, using, impedance method. The impedance probe method is the simplest and probably the cheapest of all techniques. Noninvasive probe arrangements have been conceived in a flush configuration mounted with the pipe wall, with advantage that they do not disturb the two-phase flow distribution.

Flush mounted impedance probes formed by a pair of electrodes are still been used along with flow data statistical processing for both vertical as well as horizontal gas-liquid flow [5–8]. This simple configuration is known to be accurate to indicate the average void fraction as long as the void fraction is cross-section uniformly distributed. However, non-uniform cross-section void fraction distribution changes the instantaneous signal, giving rise to erroneous indication of the actual average void fraction.

Two-phase mixture impedance technique can be basically divided in two other types: the resistive and the capacitive impedance technique. As a proposed solution, a single pair of electrodes sensor is required to eliminate the misreading due to that void fraction non-uniform distribution problem. Later, other studies were carried out in connection with the determination of instantaneous signal response to void fraction wave propagation.

Electrical impedance technique can also be applied to the liquid-liquid mixture for mass content determination [7-8]. The authors obtained a transference function of the mean electrical conductivity of different ethanol and gasoline blends at several temperatures.

Capacitive sensors are suitable for many applications and its success is associated to the electrodes geometry and flow direction. Literature presents many studies in which it is clear the dependency of the system characteristics, temperature, and the probe geometry and measurement technique. So, the first step for an experimental study of impedance sensor for void fraction measurement is the choice of the best sensor type, geometry and measurement technique for the system characteristics.

Three main techniques for void fraction measurement are commonly used for sensors calibration: radioactive absorption and scattering, direct volume measurement by quick-closing valves or mean density variation technique.

The sensor developed operates based on the dissimilarity of electrical properties of the liquid and vapor demineralized water. According to the operational frequency of the signal applied between the electrodes along with the knowledge of the electrical properties of the fluids, the average dominating impedance of the two-phase mixture filling in the cross-section may be either resistive, capacitive, or both. The sensor analyzed in this study operates in the capacitive range. The elementary electrical model of the sensor and the measuring system that operates without electrolysis near electrodes surfaces can be compared to a parallel RC circuit.

A parallel RC circuit analysis shows in a simple way that, for the resistive operating range, it is possible to associate the overall two-phase mixture resistance with the corresponding electrical average conductivity, as follows:

Fluid capacitance is strongly temperature-dependent. To get around this problem, a common technique is to work with a dimensionless capacitance rather than the absolute value so that the temperature influence is diminished, if not eliminated. Although the use of dimensionless capacitance use, another mathematical correction must be applied to the sensor signals guaranteeing the less temperature effect influence as possible. The dimensionless capacitance is the ratio between the actual two-phase water-steam capacitance at the same temperature. By taking regular water electrical properties (dielectric), one can estimate the operating frequency of the applied signal, which results in a range, for capacitive impedance measurement, $f \approx 1$ MHz.

2. EXPERMENTS AND METHODS

2.1. Natural Circulation Circuit (NCC)

The natural circulation circuit composed by glass Pyrex tubes of 38 mm internal diameter, 2.6 m height, with an upward vertical pipe where a heat source section with a 4.5 kW electrical resistance is located, and a vertical downward pipe where a spiral heat exchanger removes part of the total heat. The capacitance sensor for void fraction measurement is located at the vertical upward pipe above the heating section as can be seen in Fig. 1.

The expansion tank absorbs the flow density and pressure variation, and it is connected to the inferior section point. The superior expansion tank nozzle keep opened to atmosphere permitting the circuit run at atmosphere pressure. Al the circuit is not thermally insulated permitting the visualization of all circuit sections.

The boiler section is an electrical resistance is controlled by a voltage controller that makes the power control from zero to about 4.5 kWe. Temperatures are measured in 16 points along the circuit, and T type thermocouples have been used. There are two points of surface temperature measurement and 14 points of internal flow temperature measurement. There are two points of pressure measurement made by piezoelectric transducers. All data are acquired by a 32 channels acquisition data system. Before, the secondary flow from heat exchanger is monitored by two points of temperature and flow measurement.

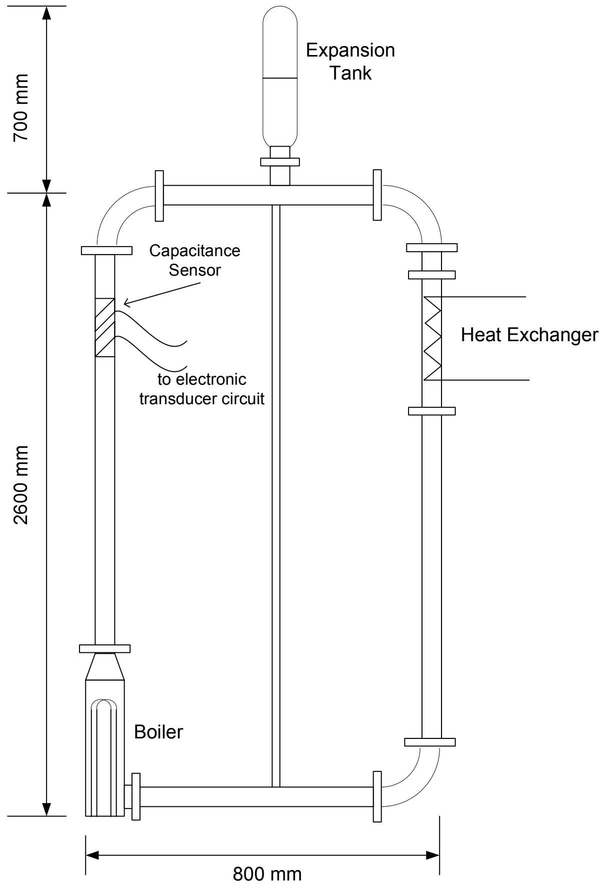


Figure 1. Schematics of the natural circulation.

2.2. Test Facility and Capacitance Sensor Calibration

A test facility was designed and constructed in the Thermohydraulics Laboratory of CEN/IPEN/CNEN-SP for void fraction sensor calibration, allowing controlled conditions of all parameters involved to have uncertainties as low as possible. It is composed by a mobile light steel structure vertically assembled to install the components and equipment used in the experimental trials, as can be seen in Figure 2. The test facility is composed of a metal frame that supports a set of bubble generator at the bottom, the glass tube containing the sensor impedance electro-pneumatic quick-closing valves at the ends of the tube, the water tank on top, a panel control valves with actuators, air flow meters (rotameters), and control valve compressed air flow. The main parameters of the test facility are:

- Height : 1770 mm
- Glass tube height : 1410 mm
- Glass tube internal diameter : 38 mm
- Compressed air flow rate : 0 to 20 Nl/min
- Void fraction range : 0 to 50 %

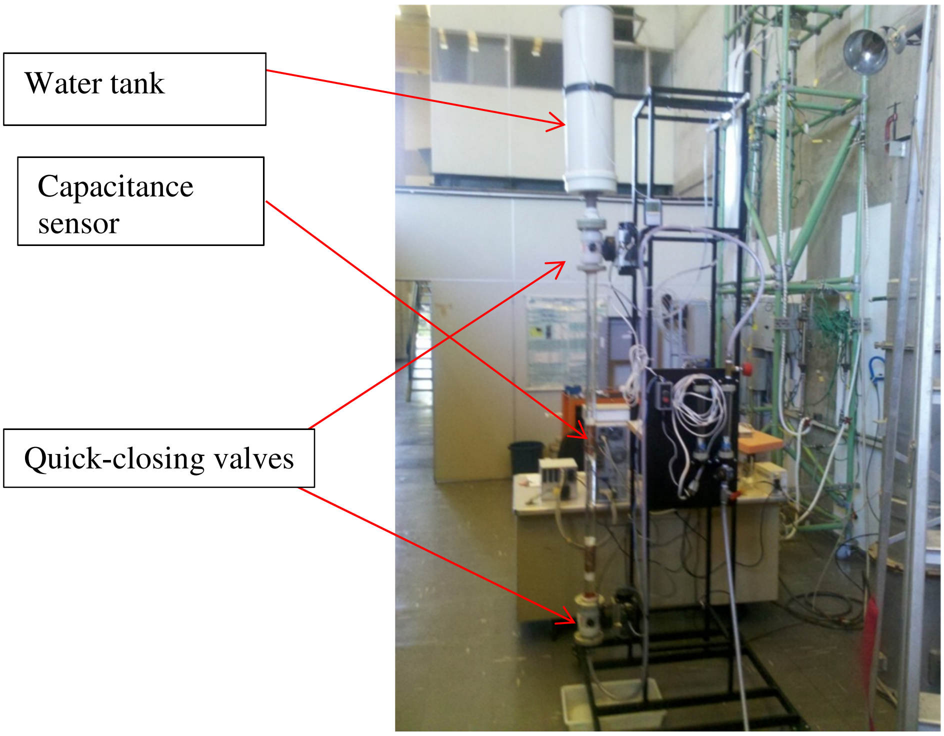


Figure 2. Test facility for capacitance sensor calibration assembling.

A capacitance sensor was designed and tested for void fraction measurement, as can be seen in Fig. 3. A copper tape coating is wound around the tube which has an i.d. of 38 mm. Electrode 1 makes three complete revolutions around the tube, electrode 2 only two. The pitch of the helix is πD, hence the active length of the sensor is 2πD (~ 4 dia). The shield electrodes fix stray capacitance and make an analytical approach of the helical cross-capacitor possible. The guard electrodes are connected electrically to the two shield electrodes. Special dual cables with characteristic capacitance of about pico-Faradays (10^{-12} F) are used to connect the electronic circuit to the shield electrodes. This arrangement permits a capacitance measurement independently of the length of the coaxial leads and external fields.

For the natural circulation circuit where the capacitance sensor is mounted, the void fraction range varies from 0 to about 60%, as revealed by the simulation results from RELAP5 [2]. The actual volumetric void fraction will be measured by two different techniques, which is going to be considered the calibration standards within this project scope. Two techniques are going to be considered as the actual average volumetric void fraction measurement: the first one is the gravimetric method (GM), because the liquid at rest, resulting in a small pressure column oscillation, provide accurate measurements and furnishing small measurement uncertainties (less than 5% according to literature).

The second standard technique is based on the use of existing well posed prediction theoretical models for a vertical column two-phase flow.

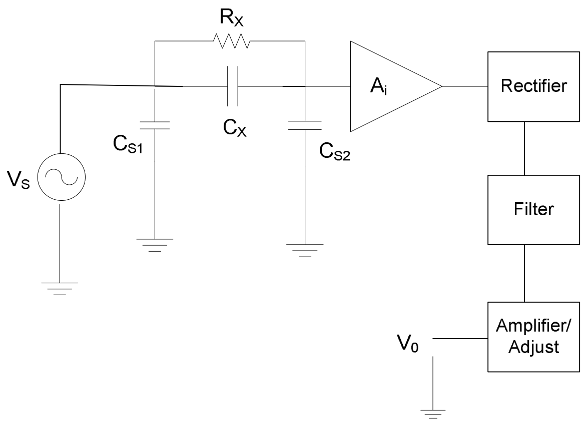
Figure 3. Capacitance sensor flush mounted on test facility.

2.3 Electronic Demodulation Circuit

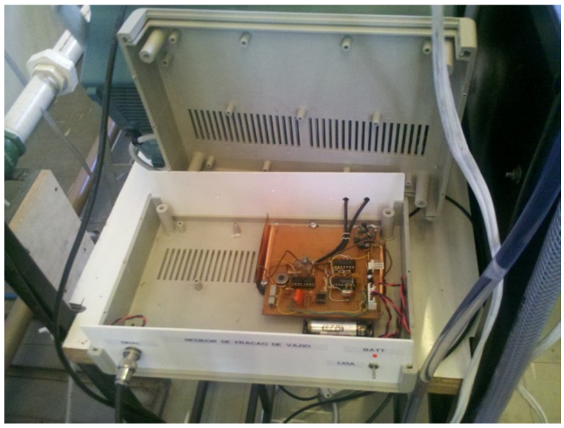
An electronic circuit was designed and constructed to make the capacitance signal transduction to an outlet signal (V_0) varying from 0 to 10V DC, corresponding to the void fraction variation from 0 to 100%.

As can be seen in Fig 3 (a), the electronic circuit consists on a signal generator which furnishes a sinusoidal wave, 10 Vpp/1.0 MHz signal that modules a current source signal that is applied to the dual helical electrodes capacitance sensor. The two-phase mixture capacitance (C_X) variation into the vertical tube produces a signal that is amplified, rectified and filtered to a 100 Hz signal (V_0) that, finally, is amplified and adjusted to be measured by a data acquisition system. The electronic circuit module is connected to the capacitance sensor by coaxial cables with low capacitance. The electronic demodulation circuit is composed by three parts: the wave generation circuit, the current generation circuit, and the signal demodulation circuit.

The wave generation creates the wave signal with amplitude and frequency to be followed by a current generation circuit that generates the signal with amplitude, frequency and relatively high current to be applied to the electrodes (emission electrode). The receptor electrode receives the signal and so, it is demodulated and filtered in the demodulation circuit. The Fig. 3 (b) shows the electronic circuit assembled.



(a)



(b)

Figure 3. Electronic circuit; (a) block diagram, (b) visualization.

3. CAPACITANCE SENSOR MODEL

3.1 The Capacitance Sensor Electrical Model

Capacitance sensors have been modeled by many authors, and some analytical solutions were obtained for specific flow conditions. There are many works in which the capacitance sensor was modeled, and some analytical solutions were obtained for specific flow conditions.
Geraets and Borst (1988) [4] show that, for a simplified electrode configuration compound of two concave flush mounted electrodes, the capacitance and electric field distribution can be calculated by Laplace equation in a cylindrical coordinates as follows:

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{1}{r^2}\frac{\partial^2 V}{\partial \phi^2}+\frac{\partial^2 V}{\partial z^2}=0 \qquad (1)$$

where, V is the potential distribution, r is the radial direction coordinate, z is the axial direction coordinate, and ϕ is the circumferential direction coordinate.

A dimensionless capacitance has been purposed [10] as a way to avoid some fluid properties influences on the calibration curve. It can be describe as follows:

$$C^* = \frac{C_x - C_G}{C_L - C_G} \qquad (2)$$

where, C^* is the two-phase measured capacitance, C_G is the pure gas filled capacitance, and C_L is the pure liquid filled capacitance.

As the capacitance (C) is proportional to the electronic circuit signal (V) it is possible to write a dimensionless signal (V^*) as follows:

$$V^* = \frac{V_x - V_G}{V_L - V_G} \qquad (3)$$

where, V_x is the voltage signal from electronic circuit for a given void fraction, V_G is the voltage signal from electronic circuit for gas filled, and V_L is the voltage signal from electronic circuit for pure liquid filled.

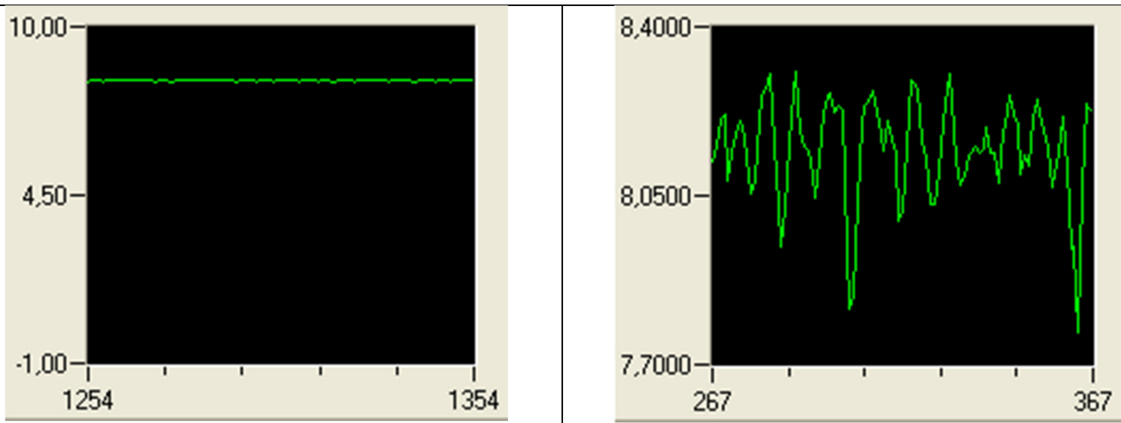
The calibration curve was obtained correlating the dimensionless signal (V^*) with measured void fraction (a) using two different techniques: the gravimetric method, and the quick-closing valves method. The gravimetric method for void fraction measurement is based on density variation of two-phase flow column, and the quick-closing valves method is based on the direct measurement of air and water volumes by interrupting the two-phase flow.

4. RESULTS

As preliminary result, a series of tests were carried out in order to obtain a calibration curve of the capacitance sensor for dispersed bubbles and slug flow regimes. The gravimetric method was used to measure void fraction of dispersed bubbles flow regime ($0 < \alpha < 15$ %), and the quick closing valves was used to measure void fraction of slug flow regime ($15 < \alpha <$ 45 %).

The average temperature of water during testes was 25 ^{o}C, and pure gas (air) capacitance measured on the test section at 25 ^{o}C was 4.5 pF and the average pure liquid (demineralized water) capacitance measured at 25 ^{o}C was 25 pF.

The typical signal from electronic circuit for bubble and slug flow conditions can be seen in Fig 5.



(a) (b)

Figure 5. Typical electronic circuit Signal (V) x Time (s); (a) bubble flow, (b) slug flow.

Considering that the air capacitance does not change considerably with temperature, and correcting the water capacitance, the correlation obtained or capacitance sensor calibration curve can be seen in Fig 5. It was obtained by associating the dimensionless signal (V*) and the average void fraction measured (α).

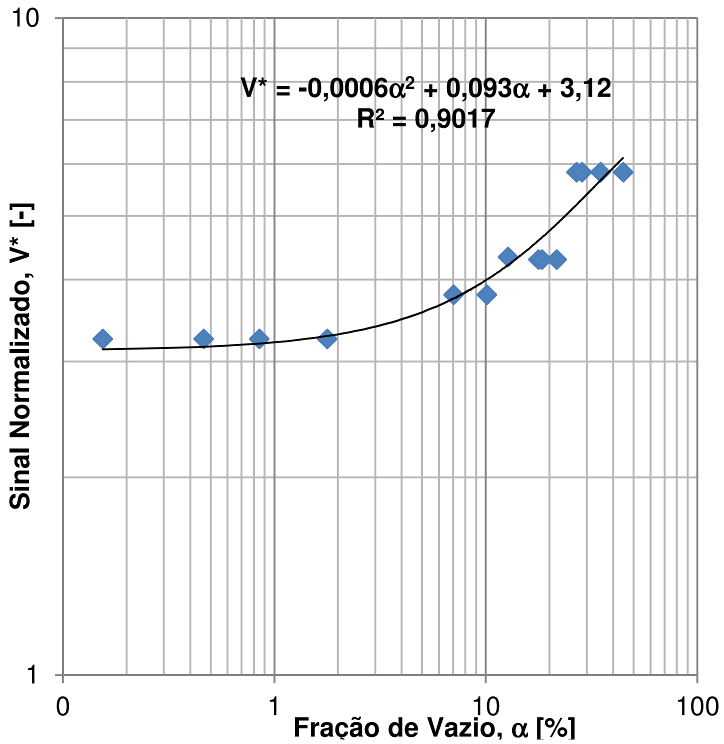


Figure 6. Calibration curve of capacitance impedance sensor ($0 < \alpha < 45\%$).

Calibration curve can be well correlated as a logarithmic curve as shown in Fig 5. The uncertainties for direct void fraction measurements is less than 1%, and the calibration curve showed low dispersion as one can see. Uncertainties are mostly related to the both direct void fraction measurement, gravimetric and quick closing valves as mentioned in [7]. The results obtained revealed to be satisfactory, but new adjusts in electronic circuit because is possible to verify low sensitivity at bubble regime compared to slug flow regime.

The next step on sensor development is to make corrections on electronic circuit and to make it available to the void fraction measurement on the natural circulation circuit by carrying out the dynamic calibration or the calibration with vapor-water or air-water flowing into the test section. A special test section has been mounted to permit the use the quick closing valve calibration technique. It will permit to obtain more realistic void fraction values, and more realistic calibration curve.

5. CONCLUSIONS

The present work shows the design, construction and preliminary tests of a capacitance sensor for void fraction measurement in a prototype of a natural circulation refrigeration loop designed to simulate a nuclear reactor cooling circuit. The capacitance sensor has being designed to measure bulk void fraction on a vertical upward two-phase flow section, and previous results show that, although a low dispersion calibration curve was obtained, it must to be enough sensitivity at bubble regime to detect the void fraction with uncertainty level sufficient to compare results with the data obtained by simulations.

Next research step consist on sensor dynamic calibration to obtain a well-adjusted calibration curve and tests to form a data bank that will permit comparisons and data use by the simulation techniques used in the project.

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