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TMI DEFUELING PROJECT FUEL DEBRIS REMOVAL SYSTEM[a]

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ABSTRACT

The Three Mile Island Unit 2 (TMI-2) pressurized water reactor loss-of-coolant accident on March 28, 1979 presented the nuclear community with many challenging remediation problems; most importantly, the removal of the fission products within the reactor containment vessel. To meet this removal problem, an air-lift system (ALS) can be used to employ compressed air to produce the motive force for transporting debris. Debris is separated from the transport stream by gravity separation. The entire method does not rely on any moving parts. Full-scale testing of the ALS at the Idaho National Engineering Laboratory (INEL) has demonstrated the capability of transporting fuel debris from beneath the LCSA into a standard fuel debris bucket at a minimum rate of 230 kg/min.

DESCRIPTION OF THE ACTUAL WORK

Several techniques, systems, and tools were employed for the recovery and packaging of the post meltdown configuration of the reactor core.[1,2] Particularly difficult was the removal of the fuel debris (a ceramic-like rubble[3]) from beneath the lower core support structure; the debris had resulted from rapid cooling of the previously molten UO_2 and ZrO_2. Approximately 19,100 kg of this rubble settled beneath the lower core support structure and onto the lower head of the reactor containment vessel.[4] The development and implementation of a debris collection system based on air-lift principles proved to be an effective method for gathering the fuel debris. Preparation of the containment vessel prior to implementation of the ALS included, installation of the Shielded Work Platform[4] and associated equipment, removal of nearly all of the debris above the lower core support assembly (LCSA) and boring operations[5] through the plates of the lower core support structure to provide 171.5 mm access holes to the lower head of the vessel. The ALS was developed under the pretense that these reactor vessel configurations had been achieved. Development of the ALS involved design, analysis, fabrication, and full-scale testing prior to shipment to the TMI site for use in the defueling effort.

The ALS assembly is shown in Figure 1. Primary components of the system include: (a) the lift tube and air injection section, (b) the separation chamber, (c) the articulating nozzle, (d) the stem and cleanout casing, (e) the debris bucket tool, and (f) the controls. The entire system is approximately 14.5 m long and weighs approximately 839 kg. It is suspended by an overhead crane that assists during installation into the vessel and provides elevation adjustment, as shown in Figure 2. A clamping arrangement on the top of the shielded work platform stabilizes the assembly once it has been positioned. Balance of the assembly is provided by adjustable ballast tubes attached to the side of the separation chamber.

The lift tube section of the ALS comprises 12.6 cm OD x 10.15 cm ID stainless steel hydraulic tubing measuring approximately 6 m long. A hydraulically actuated articulating nozzle approximately 0.5 m long is attached to the end of the lift tube. Air is injected through several small holes near the lower end of the lift tube through a surrounding coaxial annulus. As the air is injected into the lower end of the lift tube, a semi-homogeneous mixture of air and vessel water is produced. The gross density of this mixture is less than that of the fluid that surrounds the lift tube (primarily water) hence, the system drives towards equilibrium and the heavier surrounding fluid displaces the mixture within the lift tube. This creates an entrained flow of water into the lower end of the lift tube. By continually injecting air into the lift tube, the system continually drives towards equilibrium. This maintains the required flow through the foot of the lift tube.

Water velocities within the lift tube must exceed the terminal velocity of the debris falling through the body of water in order to transport the debris vertically through the lift tube. Stokes' Law[6] was used to calculate the approximate terminal velocity of a 25.3-mm diameter spherical debris particle of UO_2 having a density of 10.4 g/cm^3. The approximate terminal falling velocity for the design basis debris was calculated to be 2.8 m/s.

Operational characteristics of an air-lift device are a function of the quantity of air supplied. There is a minimum air volume required to produce the air-lift flow within a lift tube. Air flow above the minimum value increases the water flow to its peak very quickly. Increasing the air flow above the peak operating condition enhances coalescence of the bubbles within the lift tube, thus producing slug flow that reduces the efficiency substantially. To avoid excessive coalescence within the lift tube, air was injected though twelve 1-cm holes around the lower end of the lift tube. The

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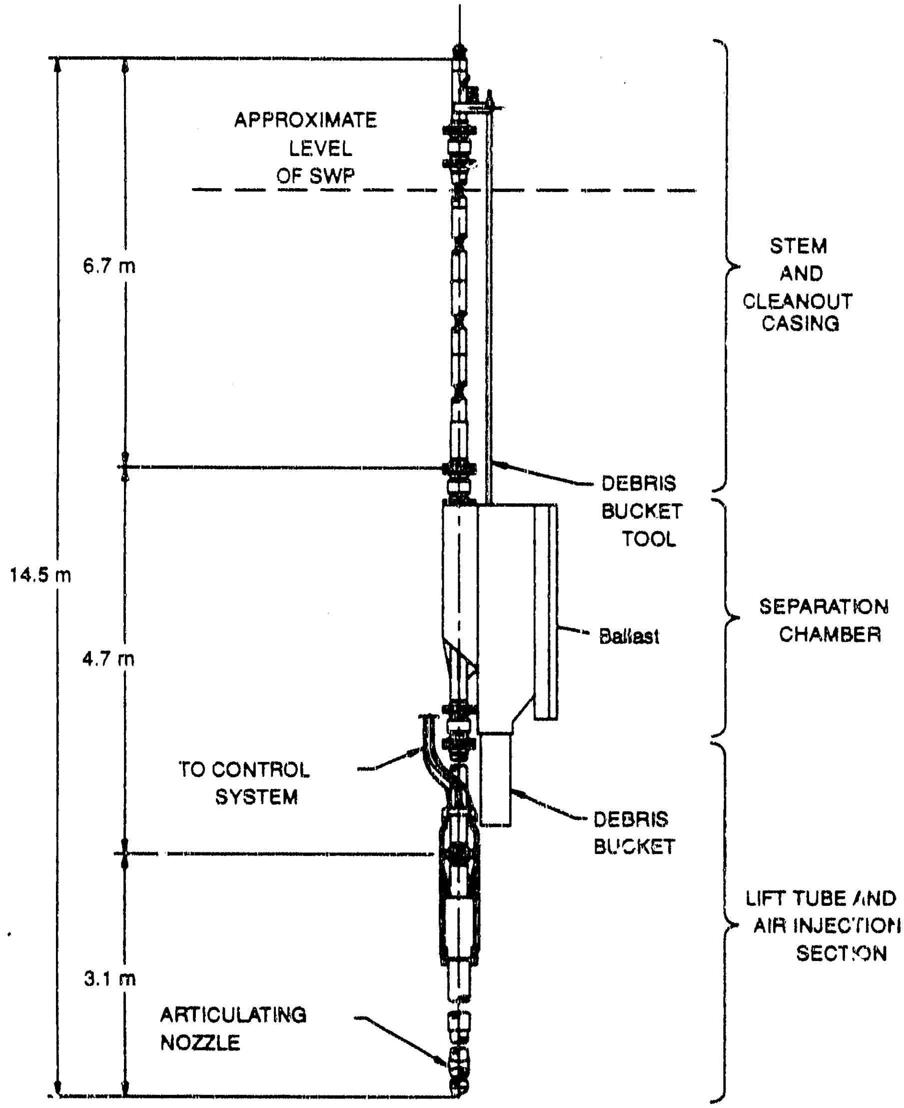

Figure 1. Air-Lift System Assembly.

DISCLAIMER

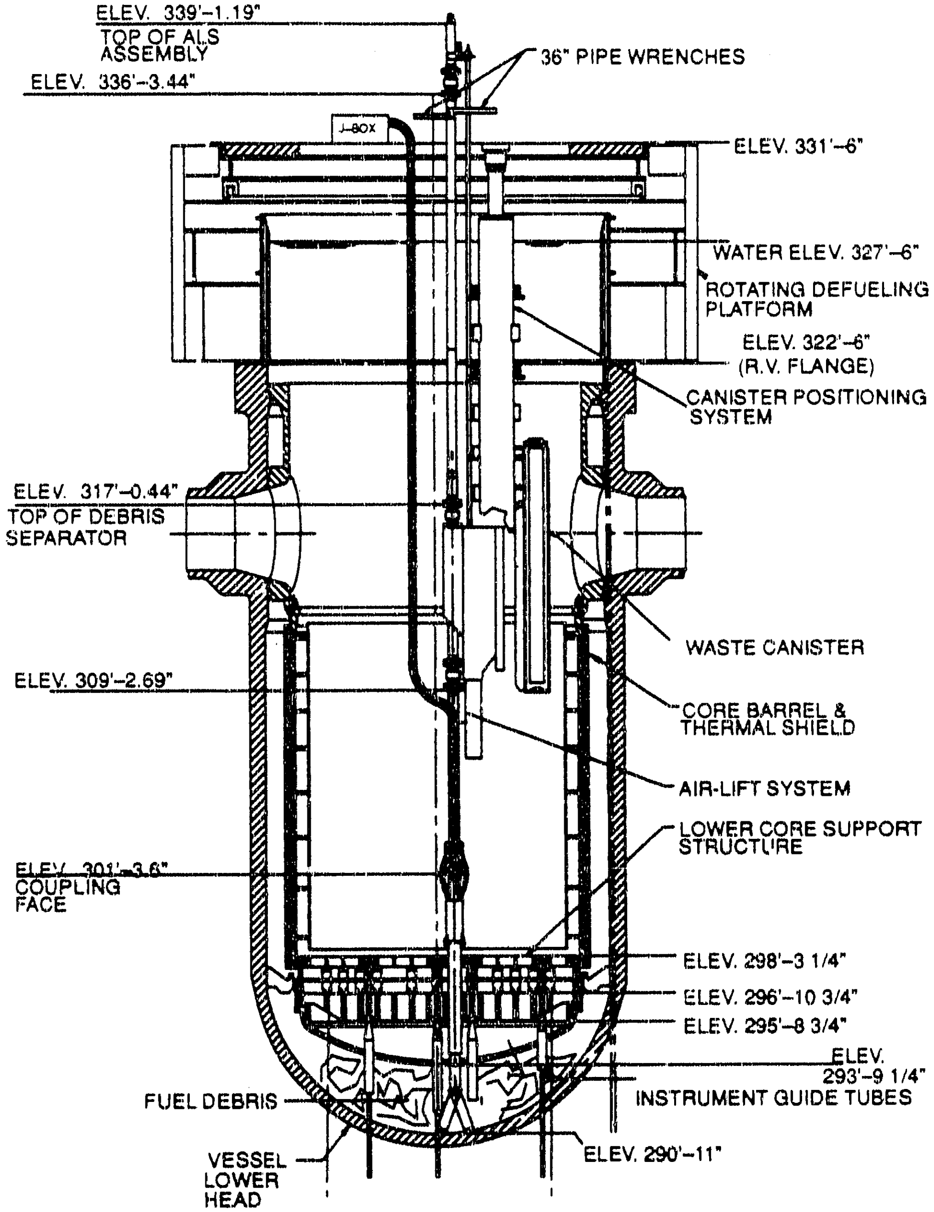

Figure 2. Air-Lift System Assembly Installation.

air flow parameters were determined using calculation methods presented in the Encyclopedia of Fluid Mechanics.[7] The air injection point was located as low as practical to develop the maximum air-lift motive force. Available literature on the air-lift technique does not describe the flow characteristics when the lift tube discharge remains below the surrounding body of water. In order to maintain adequate radiation shielding, it was essential to discharge and collect the highly radioactive particulate from the reactor at a minimum of 3 m below the surface of the reactor water level. Therefore, in calculating the operating parameters of the ALS, a 100% submergence of the lift tube was used.

Using the above considerations, the minimum air supply volume and pressure required to transport the debris through the lift tube is calculated at 2,774 L/min and 98.5 kPa. Air flow pressure can be adjusted from the J-box equipment panel, which is located on the top of the shielded work platform. The corresponding water flow rate through the lift tube is calculated at approximately 1,480 L/min at a velocity of 3.96 m/s at full flow.

A stowed drill rod casing located within the stem of the ALS is used to remove clogs within the lift tube. Drill rod casing can be lowered down through the stem from the working platform. Extensions can be added to the casing to provide the necessary length to clear clogging at the foot of the lift tube.

Separation of the debris from the air and water mixture is accomplished in the separation chamber. The chamber is designed with two connecting compartments separated by a baffle type plate, as shown in Figure 3. The three-phase mixture is discharged from the lift tube and into the bottom of chamber 1. The cross-sectional area of the chamber is 539 cm^2 and the velocity of the mixture is reduced to approximately 3.1 m/s. This allows for the air to rise to the top of the chamber where it forms a bubble dome in the top of the chamber. The air then escapes through a series of holes in the top end of the chamber. These escape holes can be adjusted to regulate the volume of air in the bubble dome. The remaining water and debris mixture flows under the baffle plate and into chamber 2. The cross-sectional area of chamber 2 is approximately 1532 cm^2 and the velocity of the flow is slowed to approximately 0.45 m/s. At the calculated velocities in chamber 2, UO_2 particles of 600μ diameter will settle into the debris bucket. The remaining water and smaller particulate is discharged back into the body of water within the vessel.

The debris bucket is a standard debris bucket designed to interface with the defueling carousel of the shielded work platform. The bucket was suspended through the bottom of the separator with the debris bucket handling tool. The bucket tool mounts on a load cell bracket that is attached to the stem. The load cell provides indication of the debris bucket weight to the operator. The bucket tool is used to move a full debris bucket from the ALS to the defueling carousel and then place an empty debris bucket into the ALS.

The lower 0.5 m of the lift tube is capable of articulating 20 degrees from centerline in one plane with the use of hydraulic cylinders and cables. This allows the ALS to gather a greater amount of material through each access hole in the LCSA. Rotation of the nozzle is accomplished by manual rotation of the stem. The separation chamber is mounted to the stem and the lift tube by rotary couplings, which allow the separator to rotate independent of the stem and lift tube. The stem and the lift tube are synchronized using a geared shaft that is mounted to the separator and geared to both the stem and the lift tube. This allows for 1:1 rotation of the stem to the lift tube while the separator remains stationary. A linear potentiometer, designed to be leak-tight, is employed to measure the nozzle articulation. Output of the nozzle position is indicated at the control panel.

The hydraulic control valves and air control valves are housed within a J-box that is located on the shielded work platform. The J-box interfaces with the local service panel of the shielded work platform and the ALS. The valve controls are located on the control panel, which is mounted to the railing of the shielded work platform. The control panel comprises the power switch interface button, emergency stop button, the debris bucket load cell reading, air pressure reading, the articulating nozzle angle reading and

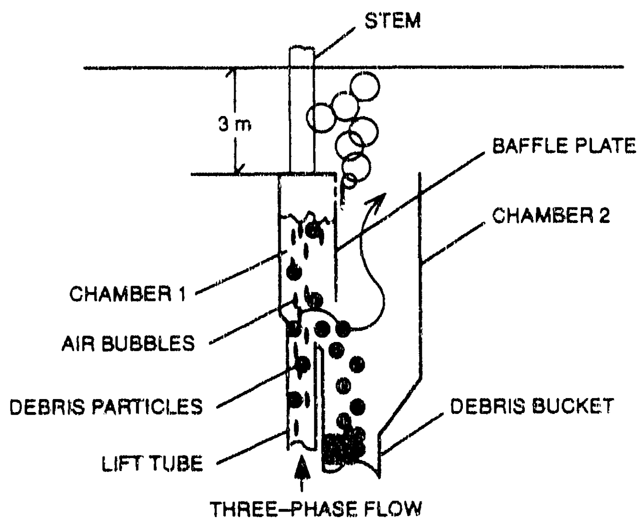

Figure 3. Separation Chamber flow path diagram.

actuation switch, the air supply button, and stall indicating lights. Set points on the load cell do not allow for the air to be supplied if the debris bucket is not in position. When the full debris bucket weight is reached, the air supply is automatically shut off.

RESULTS

Design verification and operational checkout was performed by full-scale testing of the ALS at the Idaho National Engineering Laboratory. A 10.6 m deep, 1.8-m diameter water-filled tank was used to simulate the reactor vessel environment. A mockup section of the lower core support structure was fabricated and placed in the bottom of the tank. Lead (Pb) shavings, cubes of lead measuring 2.5 cm, lead shot of various sizes and sections of 1-cm diameter stainless steel tubing, 2–5 cm in length, were placed in the bottom of the tank to represent the fuel debris. An underwater camera and recorder were used to record the installation and operation of the ALS within the test tank.

Installation and assembly of the ALS was performed outside the tank, in sections, because of overhead height restrictions. Because of its eccentric center of gravity, the centerline of the ALS lift tube and stem rests 5 degrees from vertical. As the ALS is placed into the tank, the ballast arrangement corrects the centerline to within 1/2 degree of vertical. This angle proved to be sufficient for insertion of the ALS through the access hole in the LCSA.

The articulation nozzle of the ALS was allowed to impact the simulated fuel debris pile at the full velocity of the overhead crane (approximately 1/2 m/sec). Because no damage occurred to the articulating nozzle components during this impact, the structural integrity of the articulating nozzle was proven. The system was raised approximately 6 cm from this position prior to initial startup. Power was turned on and all systems were verified prior to actuation of the air supply to the lift tube. This created hydraulic forces sufficient to transport the debris surrounding the nozzle submerged under approximately 6 cm of simulated fuel debris. Material surrounding the nozzle was entrained and transported within approximately 2 seconds. Articulation of the nozzle and rotation of the ALS was performed to gather the material within a 1 m diameter of the centerline of the ALS. Simulated debris material was entrained and transported at a rate greater than could be supplied by maneuvering the nozzle. Because of this, it was difficult to determine the actual material transport rate. It is estimated that the debris transport capacity of the ALS is no less than 230 kg/min at the operating conditions during testing.

During initial testing, it was noticed that the smaller lead shavings were being swept out of the air baffle holes at the top of separation chamber 1 (see Figure 3). This problem was sufficiently corrected by adjusting the baffle holes in the top of the ALS to form a larger bubble dome within chamber 1. It may have been advantageous to place a baffle screen at the predicted bubble dome-to-effluent interface to enhance bubble coalescence. The greater coalescence was predicted to reduce the froth within the bubble dome and eliminate any entrainment of the smaller particles. However, schedule constraints would not allow for further testing in this configuration. Debris passing into chamber 2 settled into the debris bucket as predicted; very little of the smaller debris was entrained and discharged from the separator. The debris bucket suspended within the separation chamber can be filled with debris in less than 1 minute (estimate).

CONCLUSIONS

Events during the ALS operation transpired at a very fast rate. Data recording was performed manually and was not sufficient to record all pressure, bucket weight, and ALS flow during the very short periods of operation. The debris transport rates were greater than anticipated. This may be partially due to the fact that the top of lift tube terminated approximately 4 m below the surface of the water and created greater lift tube velocities than calculated for 100% submergence. Based on these results, further testing will likely prove that the ALS is capable of transporting debris larger than a 2.5 cm cube of lead. Debris, water, and air separation techniques effectively packaged the simulated debris into the fuel bucket.

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