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# Designs for Remote Inspection of the ALMR Reactor Vessel Auxiliary Cooling System (RVACS)*

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F. J. Sweeney, D. G. Carroll,[1] C. Chen[2], C. Crane[3], R. Dalton[3],
J. R. Taylor[4], S. Tosunoglu,[5] T. Weymouth[6]

Center for Engineering Systems Advanced Research
Oak Ridge National Laboratory
P.O. Box 2008
Building 6010, MS-6355
Oak Ridge, TN 37831-6355
615-574-6162
e-mail: fjs@ornl.gov

[1]General Electric
[2]The University of Tennessee
[3]The University of Florida
[4]Martin Marietta Energy Systems
[5]The University of Texas
[6]The University of Michigan

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## Abstract

One of the most important safety systems in General Electric's (GE) Advanced Liquid Metal Reactor (ALMR) is the Reactor Vessel Auxiliary Cooling System (RVACS). Because of high temperature, radiation, and restricted space conditions, GE desired methods to remotely inspect the RVACS, emissive coatings, and reactor vessel welds during normal refueling operations. The DOE/NE Robotics for Advanced Reactors program formed a team to evaluate the ALMR design for remote inspection of the RVACS. Conceptual designs for robots to perform the required inspection tasks were developed by the team. Design criteria for these remote systems included robot deployment, power supply, navigation, environmental hardening of components, tether management, communication with an operator, sensing, and failure recovery. The operation of the remote inspection concepts were tested utilizing 3-D simulation models of the ALMR. In addition, the team performed an extensive technology review of robot components that could survive the environmental conditions in the RVACS.

## Introduction

The RVACS[1] enables passive cooling of the ALMR (Figure 1) through convective heat transfer from the containment vessel to air. Decay heat after the reactor shuts down is removed by air at ambient temperature flowing through 19 m (62 ft.) high stacks, a complex plenum, and 17 m (55 ft.) high down comer and riser cylinders surrounding the containment and reactor vessels. Temperatures of the heat transfer surfaces in the RVACS may be as high as 180° C (350° F) with radiation levels as great as 500 R/hr. Because of these hostile conditions, GE desired a method of rapid remote inspection of the RVACS, emissive coatings, and reactor vessel welds during normal refueling operations. Remote operations are needed to minimize both the number of maintenance workers and their radiation exposure.[2]

The DOE/NE Robotics for Advanced Reactors program[3] formed a team consisting of engineers from the Universities of Florida, Michigan, Tennessee, and Texas, Oak Ridge National Laboratory (ORNL), and GE to evaluate the ALMR design for remote inspection of the RVACS. The goal of the project was to design robot systems using existing technologies that could perform GE's inspection requirements for the RVACS. The project attempted to produce remote inspection systems that would also have a minimum impact on the construction of the plant. GE provided the team with CAD drawings of the RVACS, environmental conditions, and inspection task specifications.

## Description of the RVACS and Reactor Vessel Maintenance Tasks

GE specified seven tasks associated with maintenance of the RVACS: 1) inspection of the RVACS stacks, 2) inspection of the hot and cold plena, 3) inspection of the cold air downcomer annulus, 4) inspection of the containment vessel and hot air riser annulus, 5) cleaning of the hot an cold air plena, 6) cleaning of the bottom of the cold air downcomer / hot air riser intersection (the bottom of the "silo" area), and 7) inspection of the structural supports that pass through the hot and cold air plena. An eighth task involved inspection of reactor vessel welds and the emissive coatings on the inside of the containment vessel.

For design purposes, the team divided the RVACS into three areas: the hot and cold air stacks, the hot and cold air plena, and the hot air riser and cold air downcomer. Because environmental and access conditions are significantly different inside the containment vessel, designs for this area were treated separately.

**Cold and Hot Air Stacks.** The cold and hot air stacks provide the inlet for ambient air and outlet for hot air removed from the containment vessel. Cold air enters the stack through a mesh screen and travels to the cold air plenum approximately 19 m below it. Inside the cold air stack, the hot air stack carries decay heat from the hot air plenum to an outlet on the top of the stack. The temperature of the hot air in the stack is approximately 70° C (160° F), and radiation levels are expected to be less than 15 mR/h for both stacks. There are four stacks for each reactor module A cross sectional view of the cold and hot air stacks is shown if Figure 2.

GE requires that all surfaces within the stacks be inspected for dirt build-up and corrosion. Smear samples on the insides of the stacks are required to detect contamination build-up. Duration of the inspection must not exceed 24 hours for four stacks and is performed every other outage. An outage for each reactor module occurs every 3 to 4 years of operation.

**Cold and Hot Air Plena.** The cold and hot air plena join the cold and hot air stacks approximately 13 m below the reactor module grade. The cold or hot air plenum connect to the cold air downcomer or hot air riser respectively. The floor of the hot air plenum forms the ceiling of the cold air plenum. Vertical clearances in these areas are less than 3 m. In addition, sixteen reactor structural support I-beams pass through the plena. Surface temperatures in the plena range from 40 to 90° C (100 to 200° F), and the hot plenum air temperature is less than 70° C (160° F). The dose rate is expected to range from100 mR/hr in shielded areas to 500 R/hr at the containment vessel surface. Access to the hot an cold plena are available through inspection plugs located at grade level.

GE requires that all bounding surfaces in both plena be visually inspected for dirt buildup, corrosion, and structural degradation. Smear samples also must be taken. Duration of the inspection for both plena must not exceed 12 hours total. In addition any dust, foreign debris and excessive corrosion must be removed. GE assumed that dirt and dust may settle in the cold plenum area. Duration for this cleaning task is not to exceed 10 hours.

GE specified visual inspection of all 16 structural support I-beams for corrosion and degradation. the interface between the beams and the plate which separated the hot an cold plena must also be inspected to assure that proper sealing is being maintained. task duration for this operation is not to exceed 4 hours per plenum.

**Cold Air Downcomer, Hot Air Riser, and Silo Bottom.** The cold air downcomer is an annulus formed on the outer surface by the concrete "silo" and on the inner surface by the collector cylinder as shown in Figure 3. The cold air downcomer is separated from the hot air riser by insulation. the insulation has not been designed yet, but it will probably be made from layered steel or stainless steel sheets. Temperatures are expected to be 5 to 10° C (10 to 20° F) above ambient in the downcomer, with 90° C (200° F) temperatures expected directly under the containment vessel. Radiation exposures are calculated to range from 100 to 500 R/hr in these areas.

GE requires that all surfaces of the concrete silo and the insulation on the backside of the collector cylinder be visually inspected. Because the structural properties of the insulation are not currently known, GE required that this surface not be contacted by the robot. Smear sampling is required. The task is to completed within 24 hours.

Because of the possibility of collecting debris at the bottom of the silo, GE requires that any device designed to inspect the cold air downcomer also be capable of cleaning the silo bottom. Cleaning is expected to be an infrequent operation and will be conducted only on the basis of inspection results. The task is allotted a maximum of 6 hours.

The hot air riser is bounded on the inner surface by the containment vessel. The containment vessel is coated with a material to enhance the emissivity of the surface for improved heat transfer from the reactor vessel. At present, it has not been determined if additional heat transfer devices will be mounted on the containment vessel wall. The high emissivity coating is a 5 micron thick layer of oxide on the outer surface of the containment vessel and on the inner surface of the collector cylinder. Surface temperatures for the containment vessel are 180° C (350° F) and 90° C (200° F) for the inside of the collector cylinder. Air temperatures range from 50 to 70° C (130 to 160° F) with radiation levels of 500 R/hr.

GE requires that the entire outer containment vessel surface and portions of the inner collector cylinder surface be visually inspected for corrosion and to determine the condition of the emissive coating. Because of the possibility of heat transfer devices on the containment vessel wall, GE requires that the robot not make contact with this surface. The task must not require more than 30 hours for completion.

**Reactor Vessel Inspection.** The reactor vessel surface is maintained in an argon atmosphere inside the containment vessel. The inert atmosphere is to preclude any possibility of a liquid sodium reaction. Present ALMR designs specify the reactor vessel to be constructed with circumferential welds only. However, alternate designs also have vertical welds. This task requires that one third of the welds be visually inspected during an outage. Visual inspections of the area are also required to check for sodium leaks and determine the condition of emissive coatings on the outer surface of the reactor vessel and the inner surface of the containment vessel. Access to the annulus is through 6 gas lock ports, 7.5 cm (3 in.) wide by 38 cm (15 in.) long, arranged around the reactor vessel. Additional inspections of welds utilizing ultrasonic devices is also required. the surface temperature of the containment vessel is 180° C (350° F) and 180° C for the reactor vessel. Radiation exposure is calculated to be 500 R/hr.

GE required that this inspection be carried out every other outage (3 to 4 years) and requiring less than 3 hours to complete. Visual inspections require images with 25 micron resolution.

## Designs for Remote Inspection

In order to assess the possibility of performing the required maintenance tasks remotely, the team designed systems and evaluated them. The design effort was divided into eight areas necessary for remote maintenance tasks: system access and deployment, platform and motive (locomotion) design, environmental hardening, sensing, navigation and location, manipulation, communications, and tooling.

Each of the designs were evaluated by the entire team for issues such as failure recovery, current availability of components, and impact on the ALMR design. Operation of the concepts were simulated in the RVACS utilizing the IGRIP 3-D modeling package[4]. This allowed testing for interferences, reach, and we are currently investigating its use as a sensing system simulator.

As a result of the design efforts, three robot concepts were developed: a vertically mobile, rail mounted system for inspecting the hot and cold air stacks, a tracked platform with a manipulator and deployable sensor package for inspection of the cold air downcomer, bottom of the silo and hot air riser, and a small tracked vehicle for inspecting the reactor vessel welds.

**Stack Inspection System.** The stack inspection robot consists of a rail mounted support unit and a deployable inspection unit as shown in Figure 4. The inspection system is deployed and controlled using a storage rail and winch system that is be located outside the stack during inspection. The storage rail mates with the stack rail and allows the inspection system to deploy itself using gravity. The movement of the inspection system is controlled by two separate winch units. One controls the distance of the support unit along the rail while the other controls the vertical distance of the inspection unit down the stack.

The support unit, which is controlled by its winch and cable, moves along the rail and provides support to the inspection cable through a pulley. As the support unit changes position along the rail the inspection unit follows it.

The inspection unit is controlled by a separate winch and cable. In addition to following the support unit along the rail, it is capable of moving up and down within the stack, thereby controlling the position of the sensory equipment. To further refine the sensory equipment's position, the sensor package is attached to the end of a rotating arm that is capable of 180 degrees of rotation. This arm gives the sensor package greater freedom during the stack inspection. The inspection unit is also equipped with a stabilization device to prevent any swinging motion that may be induced by movement of the support unit or by air flow through the stack. The stabilization device consists of two inflatable air bladders, one on each side of the inspection unit. These bladders can be inflated very rapidly to provide compliant support to the inspection device.

Secondary support units are also provided to prevent the various cables from contacting the stack wall or becoming entangled as the inspection system follows the rail around the stack circumference. There are a total of twelve secondary support units. They are tied together so they evenly distribute themselves as the main support unit moves along the rail.

While the support and inspection units are the same for both the cold air downcomer and the hot air riser, the rail system is different in each case. The cold rail is actually divided into two pieces. Each follows a path half way around the circumference of the stack to reduce the distance the inspection units need to travel in one pass . Thus, inspection of the cold air downcomer consists of two passes, each inspecting half of the stack. This rail would be installed above the RVACS intake port to reduce its involvement with the air flow.

The rail consists of one 5 cm (2 in.) pipe and two 2.5 cm (1 in.) pipes configured in a triangular shape. They will be installed with a five degree incline to allow gravity to pull the inspection system along the rail.

**Plena and Riser Maintenance System.** The design for the plena inspection device (Figure 5) consists of three distinct systems. The first, the primary robot, is a mobile platform driven by two tracks and is designed to navigate the horizontal plena region. The primary robot is deployed using a platform that carries the robot down through the plena access shaft to the access hatch. The robot then drives itself off the platform and into the horizontal plena. Located on the primary robot are a high strength vacuum, the deployment mechanism for the secondary robot, and various sensors and a serial manipulator. A container is located on the primary robot to store debris collected during plena cleaning operations. Also located on the primary robot is the spool that contains the tether for the secondary robot. To facilitate its positioning for deployment of the secondary robot, the primary robot is equipped with a docking mechanism . The mechanism prevents the robot from moving into the vertical annuli region and also reports when it is in deployment position through the use of two contact switches. The mechanism docks with two small posts mounted into the floor of the horizontal plena. These posts are removable by the primary robot if a situation requires their removal.

The primary robot also serves as a deployment platform for a second robot. This secondary robot is a much smaller platform that is driven by wheels and is designed to navigate the vertical regions next to the collection cylinder. During horizontal plena inspection the secondary robot is located on the primary robot. Each time the secondary robot is deployed it descends through the vertical region to the bottom of the silo where it travels straight across the horizontal region below the containment vessel. It is then completely withdrawn and the process is repeated at eighteen points along the circumference of the vertical region.

The robot is driven by two air motors that power the four wheels. Air motors were chosen because of the readily available compressed air needed for the vacuum system on the primary robot. The wheels are propelled so that the platform can move, inspect, and remove debris at the bottom of the silo. The robot itself has no steering capabilities. It is designed to move on a straight path once it is deployed.

The third system is tether management. This system is responsible for ensuring that the entire robot is recoverable in case of malfunction. It is also responsible for managing the multiple power and control cables so that they do not become an obstacle to navigation.

**Reactor Vessel Inspection System.** The Reactor Vessel Inspection Robot (RVIR) is a semi-autonomous vehicle which provides a mobile platform for the sensor package as well as environmental protection for all components (sensors and drive system) as shown in Figure 6. The vehicle is designed to carry one fiber optic bundle lens, a panning system, halogen spotlights, two ultrasonic test probes, and expansion volume for additional equipment. Shielding and cooling capabilities are allowed for, but will be added only as needed for specific items. The drive system will consist of two electromagnets to hold the RVIR to the containment vessel wall and two electric motors coupled to the wheels for mobility.

The RVIR consists of a main body which houses the sensor package and operating systems with two secondary bodies which house the electromagnets. The main body is sealed from the environment for ease of decontamination and to simplify cooling system design.

## Remote Inspection Impact on RVACS Design

The goal of the team was to have minimum impact on the design of the RVACS. In the course of designing and simulating the remote inspection systems, it became obvious that minor modifications to the RVACS could significantly enhance operations.

The stack inspection resulted in three minor modifications: 1) a support rail system must be installed in the cold air downcomer, 2) a second access hatch should be installed on the hot air stack, and 3) an access hatch on the cold and hot air stacks should be enlarged.

The plena maintenance system yielded two modifications: a rail for tether management should be installed on the ceilings of both the hot and cold plena, and removable docking posts should be installed at each of the vertical riser or downcomer locations for deployment of the secondary robot.

The proposed RVIR design or its alternatives place only three requirements on the ALMR design. First, the inspection access port dimensions should be at least 9.5 by 37 cm (3.75 by 14.5 in.). Second, a source of three phase power for the electromagnets and single phase power for the halogen lights must be available. Third, a source of high pressure argon is necessary to supply the vortex cooling system and the argon driven actuating motors.

## Conclusion

The results of these design efforts show that it is possible to remotely perform inspection and maintenance tasks in the RVACS. By performing these tasks with remote systems, worker exposure to potentially hazardous environments will be reduced. Our design studies also show that remote operations can be integrated into designs at the conceptual stage with minimum impact on the plant. Clearly, the proper time to include remote operation capabilities is during the design stage. It is likely that by including these capabilities in the plant, future operations and maintenance costs will be significantly reduced.

## Acknowledgments

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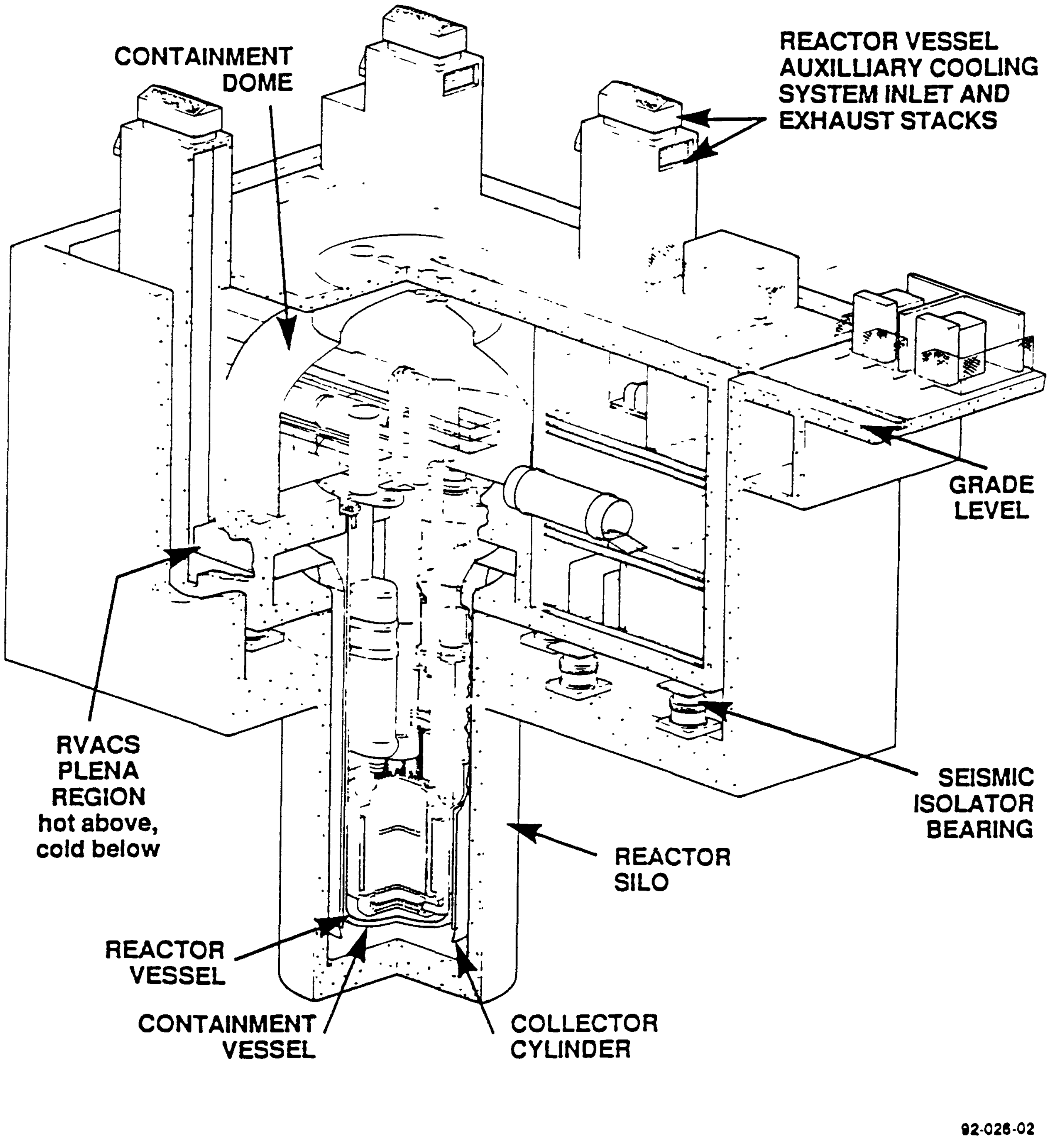
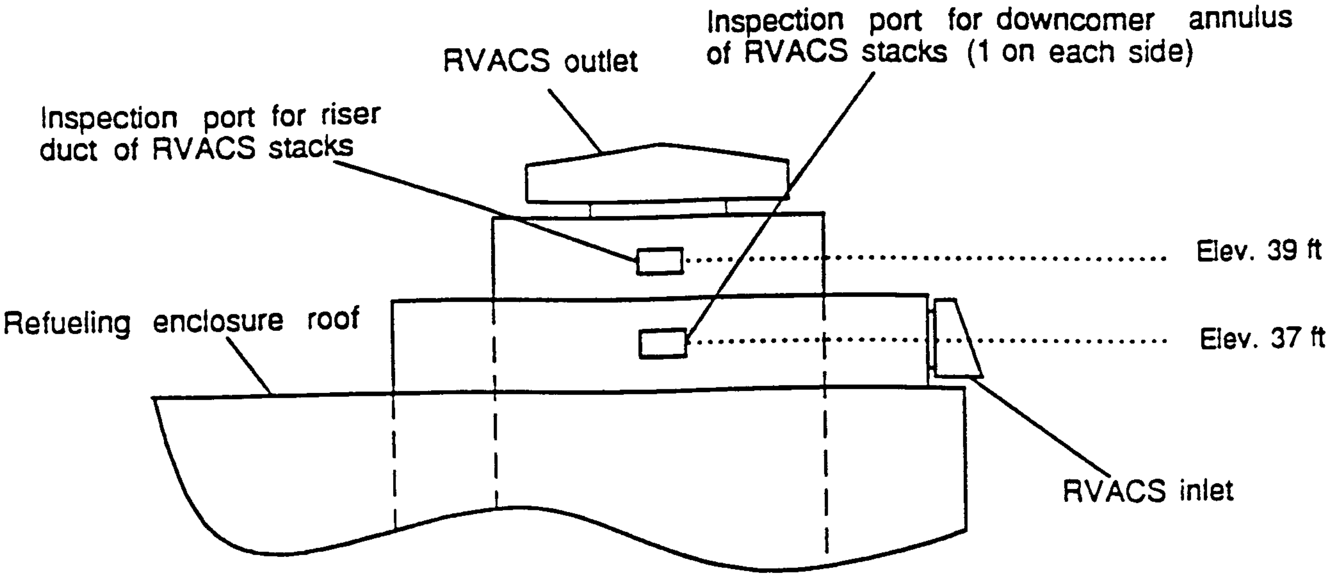


Figure 1 ALMR REACTOR FACILITY

ELEVATION - UPPER PORTION OF RVACS STACKS



CROSS-SECTIONAL VIEW - RVACS STACKS FLOW ANNULI

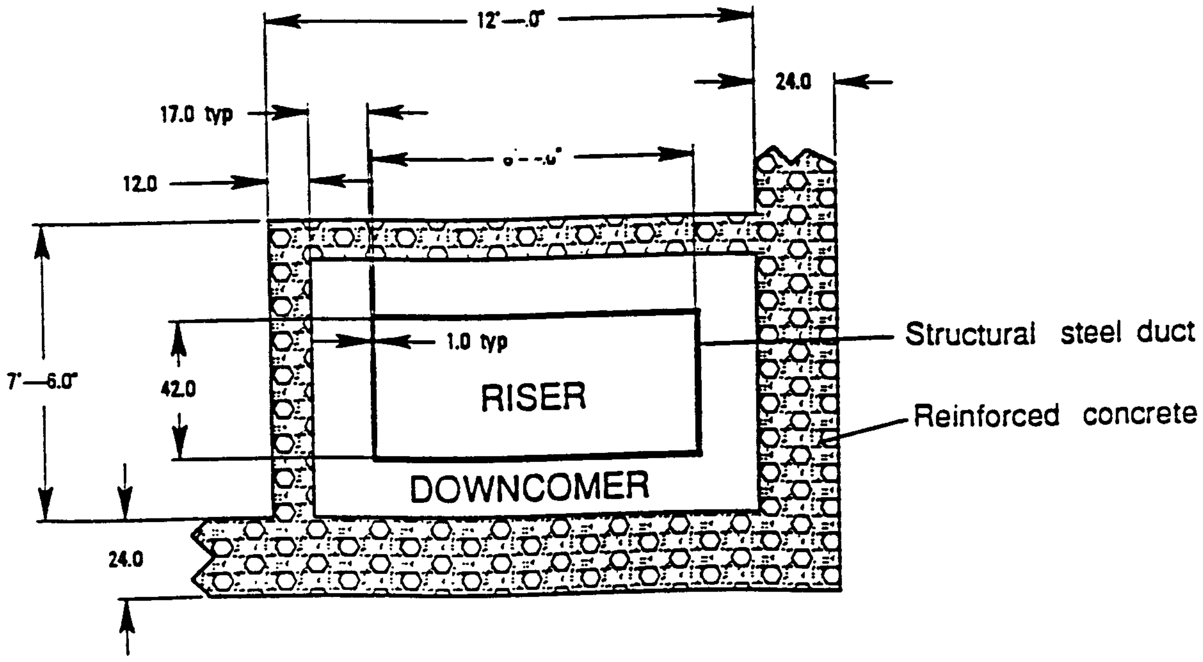


Figure 2 - RVACS Stacks Inspection Areas

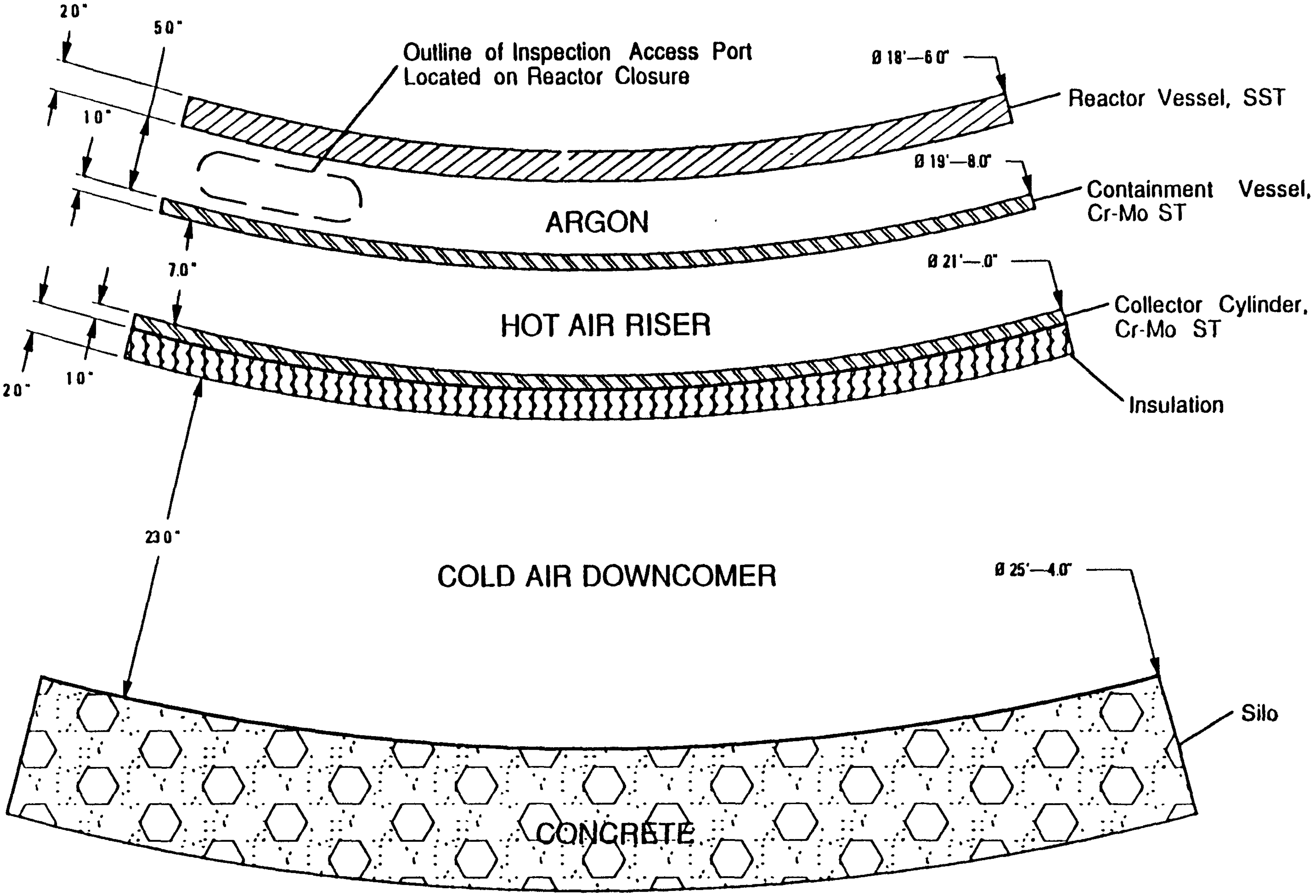


Figure 3 - RVACS Flow Annuli & Silo Cross-section

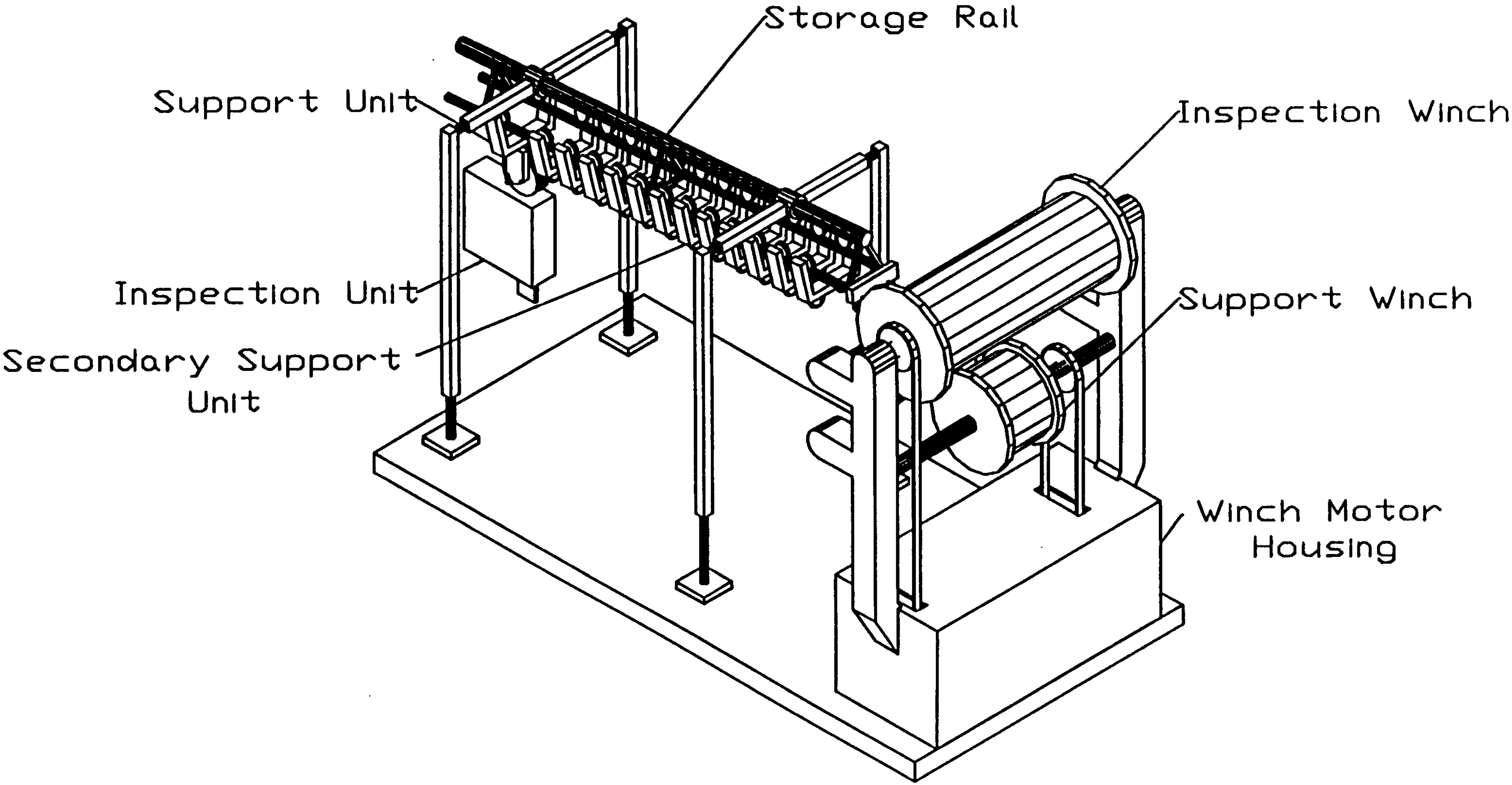


Figure 4a. Stack inspection robot.

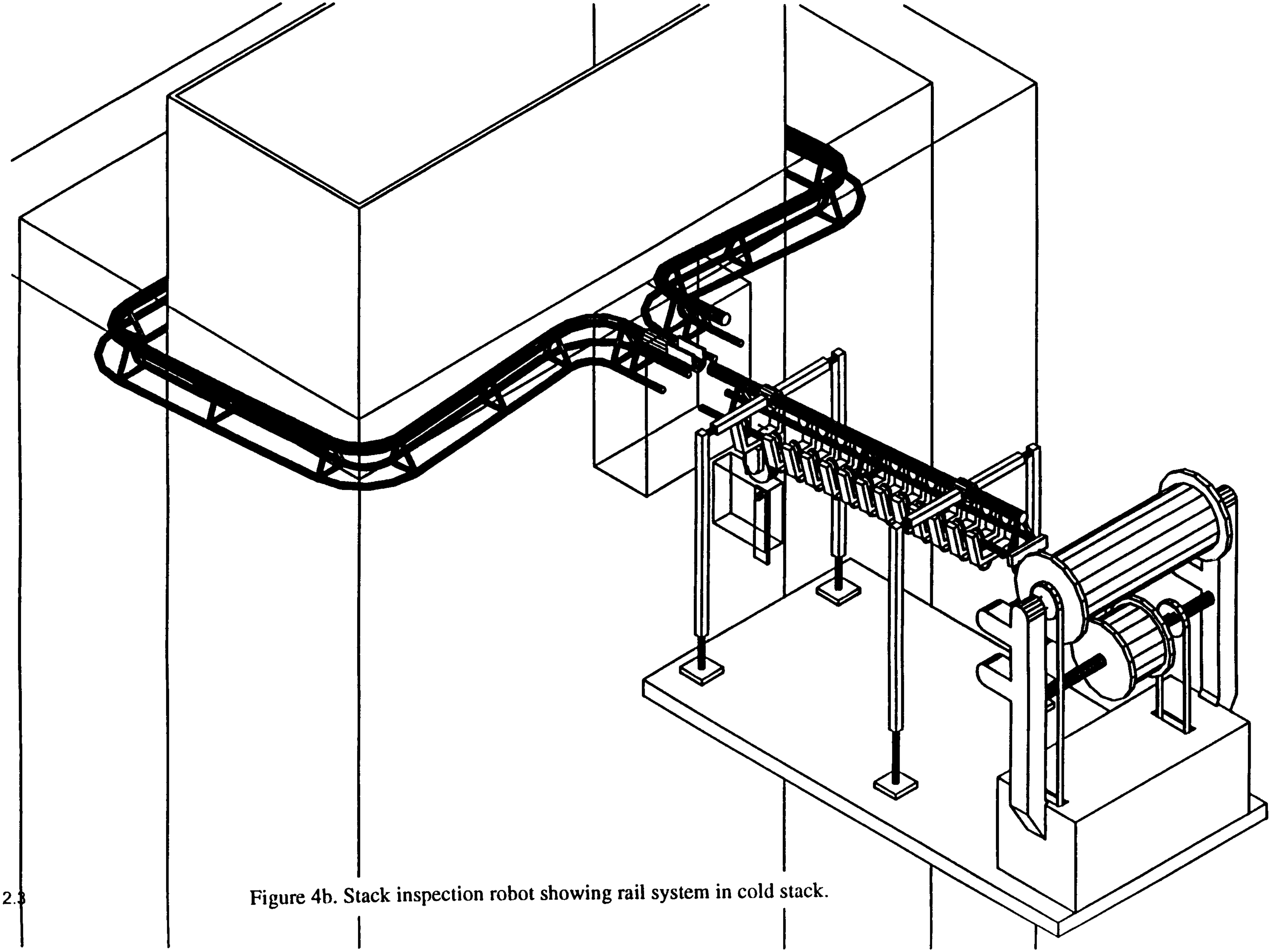


Figure 4b. Stack inspection robot showing rail system in cold stack.

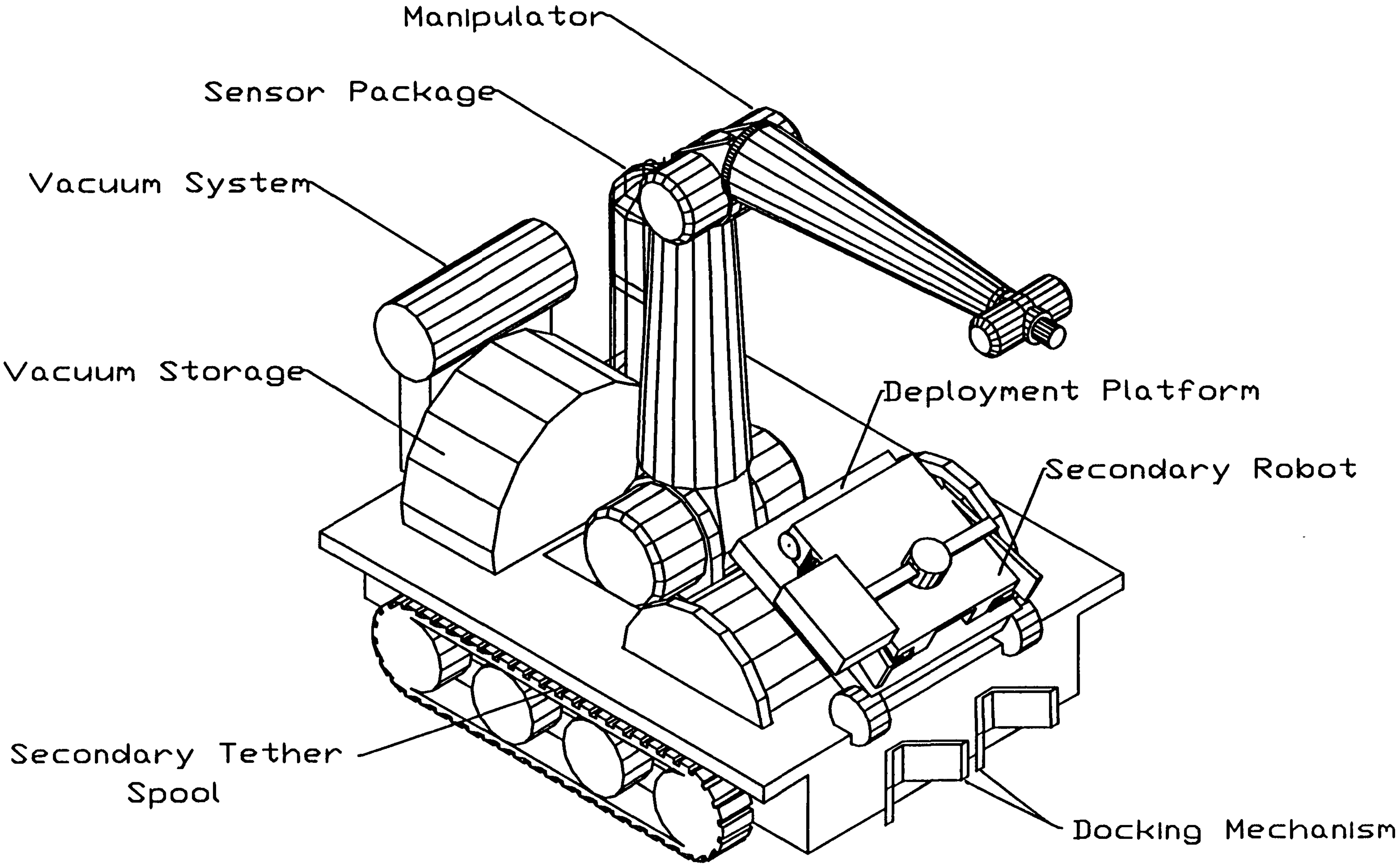
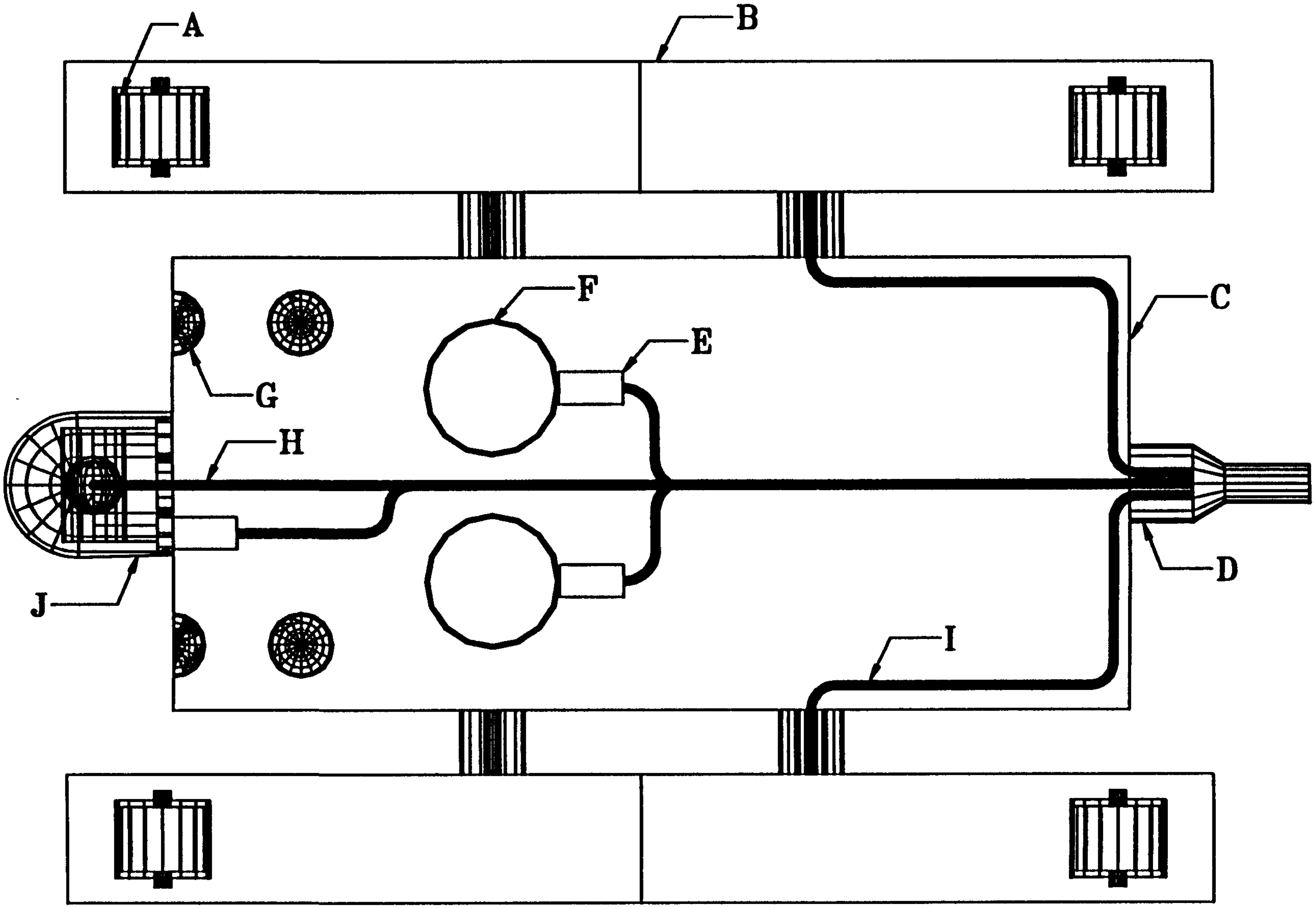


Figure 5. Plena inspection robot.

Figure 6. **Reactor Vessel Inspection Robot**



A: Wheel Spacers
B: Linear Induction Motor (SLIM)
C: Main Vehicle Body
D: Tether
E: Argon Actuators and Supply

F: Ultrasonic Transducers
G: Halogen Lights
H: Fibreoptic Cable
I: SLIM Power Cable
J: Camera Lens and Pan System