Se Approach for the Development of Internal Inspection and Maintenance Methodology of PWR RCS Primary Pipe

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***Abstract*—The Systems Engineering (SE) approach is characterized by the application of a structured engineering methodology for the design of a complex system or component. One conspicuous problem found in pressurized water reactor (PWR) plants is the primary water stress corrosion cracking (PWSCC) observed in Alloy 600 (a kind of high nickel based alloy) parts. PWSCC is considered to be caused by a mixture of three elements: high residual tensile stress on surface, material (Alloy 600), and chemical reaction with coolant. The prevention of the PWSCC can be achieved by improving one of the elements. In this paper, we applied SE methodology to specify problems, needs, requirements, and finally the solution for this issue by robotic system. Robotic devices have been used for internal inspection and maintenance of reactor primary system pressure boundary or performing remote welding and inspection in high-radiation areas. In this paper, concept of robotic device that can be inserted into the piping via Steam Generator (SG) main way to access to primary piping of pressurized water reactor (PWR) is developed based on SE methodology. A 3D model of the inspection system was developed along with the APR1400 reactor coolant systems (RCS) and internals with virtual 3D simulation of the operation for visualization to prove the validity of the concept.**

***Keywords*— PWSCC; SE approach; Robotic inspection, RCS pipe inspection**

I. INTRODUCTION

Stress Corrosion Cracking (SCC) is one of the most serious metallurgical problems facing the nuclear industry. In the 70's and 80's – Boling Water Reactor (BWR) Primary Piping; Inter granular Stress Corrosion Cracking (IGSCC) discovered in Stainless steel, and in the 80's – PWR Components; Primary Water Stress Corrosion Cracking (PWSCC) discovered in Nickel-base Alloys, like Steam Generator Tubes, Vessel Penetrations, and Nozzles. The most critical factor concerning SCC is that three preconditions are necessary and must be present simultaneously. The elimination of any one of these factors or the reduction of one of these three factors below a specific threshold level can, in principle, prevent SCC. The three necessary preconditions are: a susceptible material, a tensile stress component, and an aqueous environment. In order to prevent PWSCC from occurring it is required to detect flaws early and evaluate them in terms of their nature, size, and location. Further steps are necessary to assess (a) how severe and dangerous the flaws are in their present state, (b) whether they need to be removed by repairing the tested component, (c) if the component be scrapped, or (d) with known flaws, if the product can be allowed to go into service. These are performed through inspection and testing procedure.[1]

When applying the SE approach, the focus is on the analysis and designing of the system as a whole, as distinct from specific focus on the components or the parts. Therefore, the approach consists upon looking at a problem in its entirety, taking into account all the parts and all the parameters in an interconnected way. It requires the complete understanding on how and which part interacts with one another and how they can be combined into proper relationship to propose the optimized solution for the problem. [10]

1. REVIEW OF PWSCC

The PWSCC refers to cracks found in the Piping System of RCS, which consists of Reactor Vessel (RV), Pressurizer, Steam Generator, and Reactor Coolant Pump. Cracks appear under the presence of three factors: material, stress, and water chemistry as in Fig. 1. Moreover, the Fig. 2 shows the location of cracks that are found at Primary Coolant Loop of Reactor locations involving alloy 82/182 pipe butt welds in different designs as Table 1.

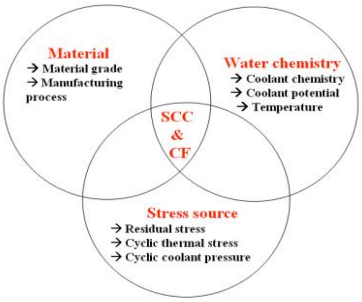

Figure 1. Factors affecting PWSCC

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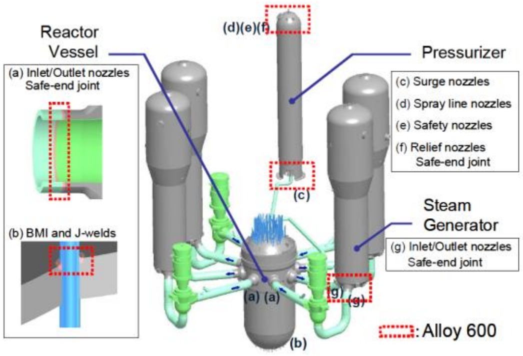

Figure 2. Location of cracks within RCS [11]

Table 1 Locations involving alloy 82/a82 pipe butt welds[4]

Location	Westinghouse Design Plants	Combustion Engineering Design Plants	Babcock & Wilcox Design Plants
Reactor Vessels			
- Inlet & Outlet Nozzles	Yes	No[2]	No
- Core Flood Nozzles	N/A	N/A	Yes
Pressurizers			
- Surge Line Nozzles	Yes	Yes	Yes
- Spray Nozzles	Yes	Yes	Yes
- Safety & Relief Valve Nozzles	Yes	Yes	Yes
RCS Piping Loop			
- SG Inlet & Outlet Nozzles	No[4]	No[4]	No
- RCP Suction & Discharge Nozzles	No	Yes[3]	Yes
RCS Branch Line Connections			
- HL Pipe to Surge Line Connection	No	Yes	Yes
- Charging Inlet Nozzles	No	Yes	Yes
- Safety Injection and SDC Inlet	No	Yes	Yes
- Shutdown Cooling Outlet Nozzle	No	Yes	Yes
- Pressurizer Spray Nozzles	No	Yes	Yes
- Let-Down and Drain Nozzles	No	Yes	Yes

1. Table does not include butt welds in instrument nozzles 1" NPS and smaller or welds that operate at less than 550°F (CRDM nozzle to flange butt welds, BMI nozzle to pipe butt welds, core flood tank nozzle butt welds).
2. One CE design plant has Alloy 82/182 welds and is evaluated with the Westinghouse design plants.
3. One CE design plant does not have Alloy 82/182 RCP suction and discharge nozzle welds.
4. One Westinghouse design plant and one CE design plant have Alloy 82/182 butt welds at this location.

2. SYSTEM ENGINEERING DEVELOPMENT

When applying the SE approach, the focus is done on the analysis and designing of the system as a whole, as distinct from specific focus on the components or the parts. The methodology starts by posing questions to determine exactly what the problem is, and what criteria should be applied to get the solution. Therefore, the approach seeks to obtain a specified combination of people and apparatus with such concomitant assignment of function, designated use of material, and pattern of information flow that the whole system represents a compatible, optimum, interconnected ensemble yielding the operating performance desired.[8][9]

2.1. Systems Engineering Methodology

At the highest level, the Systems Engineering methodology focuses on several major steps including: problem statement, identification of objectives and requirements documentation, concept generation, analysis of alternatives and trade studies, selection of primary concept, system creation, including decomposition, design, development, integration, verification and validation, and system operation and life cycle disposal. The system is then physically reconstructed from its individual components into subsystems and eventually integrated into a complete system. These steps are typically combined together in a manner that decomposes the problem into subsystem and eventually component-level "pieces" that can be handled by individual engineers. Plans are created by the System Engineer to ensure that the subsystems and overall system perform as designed (verification) and ultimately meet the desired intent of the customer (validation) by performing the desired function. [8][9]

By using the SE approach, it is possible to access the problem in a more efficient way and make the implementation of a methodology to inspect and maintain the RCS Piping easy. When analyzing the deficiencies in the RCS piping, and combining those with opportunities, the output will be the methodology for inspection and maintenance. In a first simplified view, the problem can be stated as shown in Fig. 3. [1]

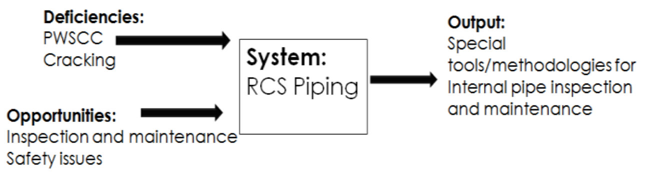

Figure 3. RCS Piping Input/ Output Diagram

The simple flowchart is shown in Fig. 4 represents decisions and actions towards the RCS Piping inspection and maintenance process. In this chart, firstly it is necessary to verify the existence of crack in the pipes. The verification can be done by many ways, section 2.2. Once a crack is diagnosed, it is necessary to determine the size of the flaw. Top- level flow diagram is shown in Fig. 5, and the V-Model for RCS Piping inspection and maintenance is shown in Fig. 6. [2][8][9][10]

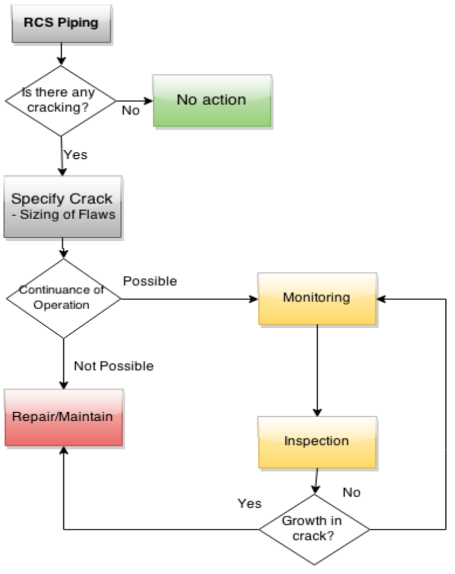

Figure 4. RCS Piping Inspection and Maintenance Flow Chart

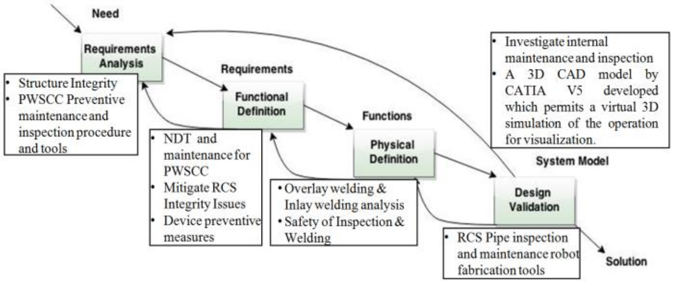

Figure 5. SE Method Top-Level Flow Diagram [9]

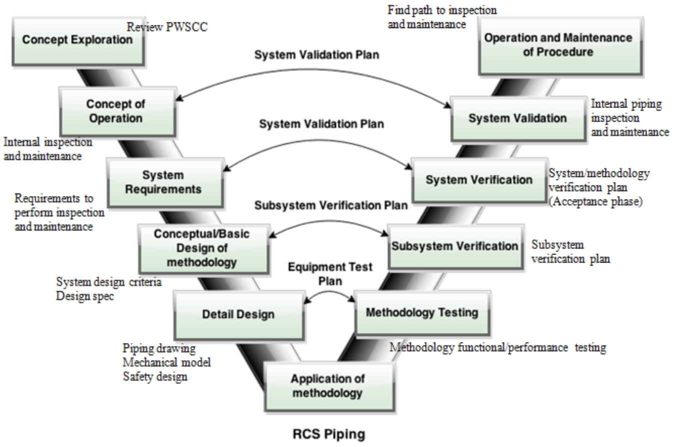

Figure 6. V-Model for RCS Piping inspection and maintenance [2][8]

2.2 Systems Engineering requirements

The section XI provides requirements for examination, testing, inspection of components and systems, and repair/replacement activities in a NPP. The rules of Section XI constitute requirements to maintain the NPP and criteria to return the plant to service, following plant outages. The rules of Section XI include Owner responsibilities and Authorized Nuclear In-service Inspector duties. The aim of section XI rule is to main conditions defined in section III, i.e. the system or component manufactured in accordance with rule given in section III shall maintain its integrity according to XI inspection and maintenance rules

2.3 Modeling of PWR RCS: 3D Model

A 3D model of RCS using CATIA V5 is shown in Figs 7 and 8 that allow a virtual 3D simulation of the operation. This approach allows a virtual walk through to verify the proposed RCS inspection system. Fig. 9 shows detail of nozzle weld inspection arrangement of robot and control.

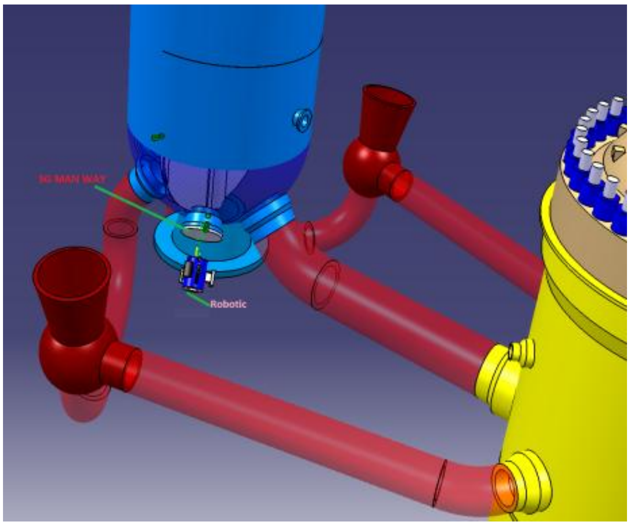

Figure 7. A 3D model for RCS and robotic at man way (CATIA V5)

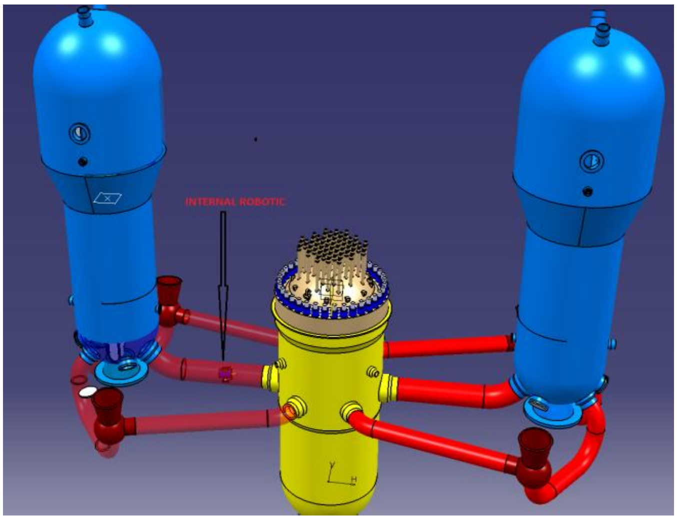

Figure 8. A 3D model for RCS and robotic inside hot leg (CATIA V5)

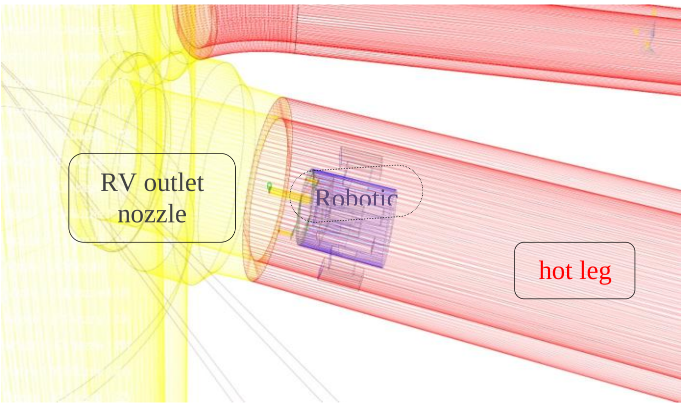

Figure 9. Internal robotic inspection at weld position (CATIA V5)

2.4 System Engineering Development phase: internal inspection and maintenance technique

2.4.1 Remote welding robotic: Remote Repair

The principal component of the system is the SDC Robot, which functions as both the delivery vehicle and the tool. It is a radiation-hardened magnetic crawler, resembling the form factor of a snake. It is umbilical-deployed to nearby the subject position, and then crawls along a horizontal, vertical, or curved surface to the work site. It can navigate through bores as narrow as 2.1”, and over bumps at high as 0.4”. Once the SDC arrives at the subject position, an onboard radiation-tolerant camera deploys to survey the area, and facilitate operation. Then a grinding wheel preps the surface for welding. Following the automated weld process, an EMAT UT array performs a volumetric exam on the weld to validate results and thickness. Figs. 10 show Diakont (name of the robotic device model as well as the company) welding robot and deployment station with welding rod pusher.[5]

Figure 10. Diakont welding robot and deployment station with welding rod pusher [5]

Features of SDC robot

- Combination delivery, work, and inspection robot
- Carbide-studded drive wheels for firm traction even on slick surfaces
- Radiation-hardened for operation anywhere
- Built-in camera, EMAT UT inspection probe, grinding wheel, and welding

2.4.2 Nuclear Plant Buried Pipe Inspection

Diakont robotic inspection of nuclear buried piping using the RODIS and HERCULES in-line powered tools shows in Fig. 12 how pipes are inspected using ultrasonic (UT) method via angle-beam EMAT, 3D laser profiling, and close-up visual inspection. Through the use of Diakont’s innovative crawler-based tools, an expensive and disruptive pipe, excavation can often be avoided or minimized. [6]

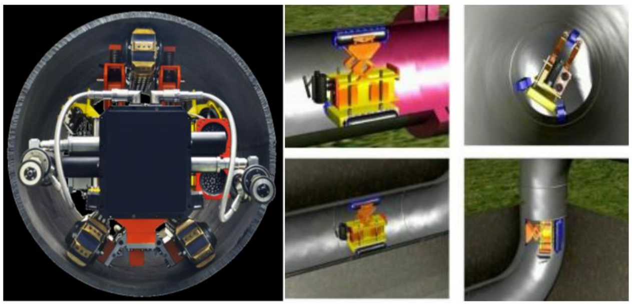

Figure 12. In-Line Inspection of Nuclear Plant Buried Piping [6]

Diakont performs direct assessment of pipes with diameters from 18”-59” of varying materials and liners, and in varying states of corrosion. The inspection technology includes defects and degradation including pitting, microbiologically-induced corrosion (MIC), flow-accelerated corrosion (FAC), SCC, and general wall thinning. Fabrication defects are also analyzed including for incomplete fusions on girth or long-seam welds, and misaligned pipe section or valve joints. Through the course of inspections, foreign objects and materials are also detected and cataloged. The RODIS and HERCULES tools navigate the majority of pipe geometry found at nuclear power plants, including vertical sections, elbows with sub-1.5D turns, T-bends, and various types of valves. Pipes are typically accessed through a disassembled check valve or man way. Once inside the pipe, the mobile robot can travel up to almost 1/3 of a mile in either direction.[6]

2.4.3 Method and apparatus for remote inspection and/or treating welds, pipes, vessels and/or other components used in reactor coolant systems.

This mobile robot system is a tool for mitigating stress corrosion cracking in reactor coolant system welds in piping and/or other components in pressurized water reactor plants. The tool is placed at the access point from outside to a pipe or vessel and crawls within the pipe or vessel to a pre-selected weld of pipe or vessel location or other component. A perspective view of the weld mitigation tool is shown in Fig. 13.[7]

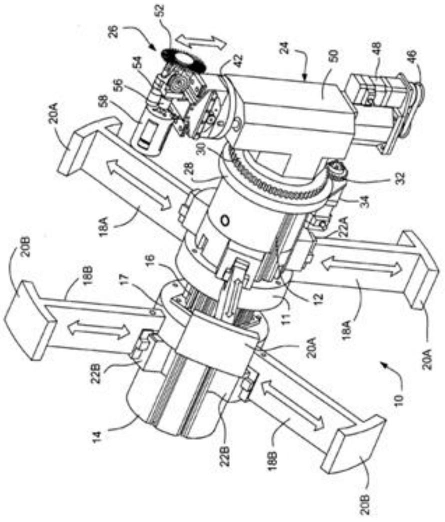

Figure 13. A perspective view of weld mitigation tool [7]

CONCULSION

The PWSCC of alloy 600 penetration nozzles of PWRs started in 1991 and continue today. Most locations of Alloy 600 nozzles/penetrations and their welds were affected by the PWSCC. The basic inspection requirement is periodic volumetric examination on the weld region during refueling outage. In this paper, we applied SE methodology to specify problems, needs, requirements, and finally the solution for this issue. We introduced three robotic devices for internal inspection and maintenance can perform remote welding and inspection in high-radiation areas. This system can be inserted into the piping via SG man way. Once inside of the RCS main pipe, robot crawler are remotely controlled (horizontal and vertical pipes incl. the elbows) to bring the inspection and repair device into the place. We investigated the effectiveness of the tools by virtual 3D simulation of PWR RCS by CATIA, and showed how to navigate this tools to weld position, and proved that this tools can perform internal inspection and maintenance of hot leg pipe and loop-closure pipe through steam generator man way.

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