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NUCLEAR POWER ENGINEERING DEPARTMENT

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AP Note-427

FEASIBILITY STUDY FOR
IN-PLACE ANNEALING OF THE
PM-2A REACTOR VESSEL

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1.0 SUMMARY

Studies of feasibility of annealing the PM-2A pressure vessel in place in order to reduce embrittlement of the vessel caused by irradiation resulted in selection of radiant heating as the most feasible method of annealing. Other possible methods of heating studied, using condensing steam, pressurized water, and hot gas, were less desirable. Advantages of the radiant heat method were: high annealing temperature (750°F) possible, atmospheric pressure, efficient use of heat where needed, controlled temperature distribution, minimum downtime, safety and economy.

A PM-2A pressure vessel mockup with a heater assembly to be installed in place of the thermal shield was designed for testing to determine axial temperature distribution at the vessel wall. The mockup testing would permit adjustment of the heating elements positioned opposite the vessel barrel wall, until the desired temperature distribution is attained. The same handling tool would be used as for the PM-2A thermal shield. Thermocouples to measure temperatures at several points on the reactor vessel wall and give remote indications for the heating assembly were designed and incorporated into the mockup.

Calculations were made of temperature distributions axially through the pressure vessel wall.

The reactor downtime for the annealing operations was estimated and the sequence of equipment installation and testing is given.

2.0 INTRODUCTION

Earlier work under Task 6.0, ⁽¹⁾ has shown that the PM-2A reactor vessel life is much less than the 20-year design life. Based on the most recent flux values presented in APAE-95, ⁽²⁾ the vessel life is only 16.9 MWYR. Due to the fact that a short life is predicted for the vessel, some means of prolonging the vessel life is necessary. One way of doing this is by annealing the vessel in place to recover the transition temperature increase brought about by neutron irradiation.

The purposes of this study were:

(1) To review the "Feasibility Study for In-Place Annealing or Replacing the SM-1 Reactor Vessel," AP Note-373, ⁽³⁾ in order to investigate how the various proposed methods of annealing could be applied to the PM-2A reactor vessel as presently installed at Camp Century.

(2) To select for further study a method of annealing which would meet the following criteria:

1. Personnel must not be exposed to hazardous conditions.
2. Annealing temperature should be 750°F or more to obtain maximum recovery and minimum re-embrittlement.
3. The heating source must be safe and well understood.
4. The heating source must not leave a residue which would interfere with future operation of the reactor.
5. Due consideration must be given to the remote location of the reactor. Annealing equipment should be compact and transportable by snow train. Downtime must be a minimum.
6. Simplicity of equipment installation and annealing procedure is of major importance.
7. The method chosen must be economically feasible.

For each of the annealing methods studied, the procedures for use in annealing operations, the equipment required, and advantages and disadvantages are defined. It was not considered necessary to repeat the detail analysis of each method because this information is covered in AP Note-373 ⁽³⁾.

Any difference in arrangements resulting from the structural differences between the SM-1 and the PM-2A reactors does not alter the evaluation of the annealing methods outlined.

(3) To conceptually design the components or select equipment required for annealing.

(4) To provide an annealing schedule.

As a guide to establishing the criteria above, some pertinent statements in ASME 61-WA-332, (5) "Effects of Nuclear Radiation on the Properties of Reactor Structural Materials" are quoted below:

"It is apparent that for those nuclear plants which operate at 510°F or below, and for which the anticipated neutron exposure of the pressure vessel will reach a total of $1 \text{ to } 2 \times 10^{19} \text{ n/cm}^2$, the increase in Nil-Ductility-Transition Temperature must be considered in establishing reactor operating procedures."

"With 600 to 750°F heat treatments, essentially complete recovery is attained within a 20 to 24 hour period."

"Annealing temperatures of 750°F or more are required to eliminate the re-embrittlement effect."

"In view of the large transition-temperature increases produced by moderate neutron dosages, the development of a practical method for recovering the initial material properties is of great interest."

STEAM: 1600 PSI - 610°F (5° SUPERHEAT)
HEAT-UP 250#/HR - STEADY-STATE 50#/HR

Figure 1. Design for Condensing Steam Annealing Method

3.0 ANNEALING METHODS

3.1 CONDENSING STEAM (FIG. 1)

Procedure:

Removal of fuel elements and control rod elements:

1. Remove dished shield tank cover.
2. Remove reactor outer and inner covers.
3. Remove fuel elements.
4. Remove control rod elements.

Placing of temporary barrier:

1. Remove thermal shield.
2. Remove reactor helix.
3. Place temporary barrier at vessel inlet.

Draining of vessel and primary system to allow disconnection of steam generator skid:

1. Replace reactor inner and outer covers.
2. Drain vessel and primary loop.
3. Move steam generator skid.

Annealing:

1. Install the annealing equipment and piping as shown and complete the annealing.
2. Dismantle the annealing equipment and piping.
3. Move steam generator skid back.

Filling system with water to allow removal of barrier and replacing of reactor components:

1. Remove reactor outer and inner covers.

2. Remove barrier.
3. Replace reactor helix.
4. Replace the thermal shield.
5. Re-install the control rod elements.
6. Re-install the fuel elements.
7. Replace the reactor inner and outer covers.
8. Replace the dished cover.

Equipment Required:

Steam generator, condensate pump, pressurizing pump, temporary piping, temporary barrier, flanges, instruments and controls.

Advantages:

Uniform temperature minimizing thermal stresses.

High heat transfer coefficient. Low flow rates.

Disadvantages:

Small amount of radiation damage recovery (26% according to AP Note-273 due to low annealing temperature (610°F); high pressure; considerable amount of equipment required. The entire operation is lengthy and has many problem areas: It will be very difficult to remove and re-install the reactor helix. To move the steam generator skid will entail disconnecting primary piping. The placing of the annealing equipment may be difficult in the space available in the vapor container.

3.2 PRESSURIZED WATER (FIG. 2)

Procedure:

Removal of fuel elements and control rod elements:

1. Remove dished shield tank cover.
2. Remove reactor outer and inner covers.
3. Remove fuel elements.
4. Remove control rod elements.

SYSTEM PRESSURE 1600 PSIA - INLET 600°F - OUTLET 595°F - 350 GPM

Figure 2. Design for Pressurized Water Annealing Method

Draining of vessel and primary system to allow disconnection of steam generator skid:

1. Replace dished shield tank cover.
2. Drain vessel and primary loop.
3. Move steam generator skid.

Annealing:

1. Install the annealing equipment and piping as shown.
2. Remove dished shield tank cover to fill the system.
3. Replace inner and outer reactor covers.
4. Replace dished shield tank cover.
5. Complete annealing cycle.
6. Drain the system.
7. Remove annealing equipment and piping.
8. Move steam generator skid back.

Filling system with water to allow replacing of reactor components:

1. Remove dished cover to fill the system.
2. Re-install the control rod elements.
3. Re-install the fuel elements.
4. Replace inner and outer covers of the reactor.
5. Replace the dished cover.

Equipment Required:

High pressure steam generator, circulating pump, throttle valve, flanges, piping, instruments, and controls.

Advantages:

Thermal stresses in the primary loop are minimized.

Disadvantages:

Small amount of radiation damage recovery (26%) due to low annealing temperature (600°F); high pressure; repeated draining of system to allow disconnection and connection of steam generator skid. The moving of the steam generator skid entails disconnection of primary piping.

3.3 HOT GAS (FIG. 3)

Procedure:

Removal of fuel elements and control rod elements:

1. Remove dished shield tank cover.
2. Remove reactor outer and inner covers.
3. Remove fuel elements.
4. Remove control rod elements.

Draining of vessel and primary system to allow disconnection of steam generator skid:

1. Replace reactor inner and outer covers.
2. Replace dished shield tank cover.
3. Drain vessel and primary loop.
4. Move steam generator skid and primary coolant pump.

Annealing:

1. Install the annealing equipment and piping as shown.
2. Complete annealing cycle.
3. Remove annealing equipment.
4. Move primary coolant pipe and steam generator skid back.

Filling system with water to allow replacing reactor components:

1. Remove dished cover.

GAS: 14.7 PSIA - 770°F - 10,000 CFM

Figure 3. Design for Hot Gas Annealing Method

2. Remove reactor outer and inner covers.
3. Replace control rod elements and the fuel elements.
4. Replace reactor inner and outer covers.
5. Replace dished shield tank cover.

Equipment Required:

Gas-fired burner including supply of gas, centrifugal compressor, duct work, instruments, and controls.

Advantages:

High amount of radiation damage recovery (possibly 100%) due to the high annealing temperature (770°F). Atmospheric pressure making it safe from system rupture.

Disadvantages:

Bulky equipment which must be located in the vapor container where space could be a problem, the moving of the steam generator skid including the primary coolant pump will entail disconnection of primary piping. The possibility of residue from the hot gas is a problem.

3.4 NUCLEAR HEATING

Nuclear heating would be the simplest method of annealing. Temperature would be limited to 600°F to prevent gross boiling in core. Annealing would be done with core at low power. However, the risks of a fuel element or a primary system rupture makes the method too hazardous.

3.5 HEAT TRANSFER FLUID

Filling the reactor vessel with Dowtherm A, or other heat transfer fluid and applying heat with immersion heaters is deemed inadvisable due to the uncertainties of attaining a clean reactor after annealing.

3.6 EXTERNAL HEATING

Applying heat elements around the outside vessel wall is also found to be inadvisable due to the difficulties and hazards in removing the reactor expansion bellows, insulation, and shielding.

3.7 RADIANT HEATING (FIG. 4)

Procedure:

Removal of fuel elements and control rod elements:

1. Remove dished shield tank cover.
2. Remove reactor outer and inner covers.
3. Remove fuel elements.
4. Remove control rod elements.

Preparation for annealing:

1. Remove thermal shield.
2. Insert heater assembly.
3. Install a new dished shield tank cover with attached plastic hose for heater wires.
4. Drain the water below the dished cover and the water in the primary system.

Annealing:

1. Complete annealing cycle.

Filling system with water to allow replacing reactor components:

1. Remove the new dished cover with hose attachment.
2. Remove the heater assembly.
3. Install the thermal shield.
4. Install control rod elements.
5. Install fuel elements.
6. Install reactor inner and outer covers.
7. Install the original dished cover.

Figure 4. Design for Radiant Heating Annealing Method

Equipment Required:

Heater assembly, new temporary dished cover, instruments and controls.

Advantages:

Possibly 100% radiation damage recovery due to high annealing temperature (750°F +); atmospheric pressure, efficient use of heat where needed; controllable temperature distribution; a minimum of downtime; simple, safe and economical procedure.

Disadvantages:

None. (Based on the comparison standards used for the other annealing schemes listed.)

4.0 SELECTION OF ANNEALING METHOD

The letter "A" indicates compliance with the requirements of the criteria established in 2.0. The letters "B" and "C" indicate a relatively less compliance.

ANNEALING METHOD	Criteria No's.							Equipment Required
	1	2	3	4	5	6	7	
Steam Heating	B	C	A	A	B	C	B	B
Pressurized Water	B	C	A	A	B	C	B	B
Hot Gas	B	A	A	B	B	C	B	B
Nuclear Heating		Inadvisable for PM-2A						
Heat Transfer Fluid		Inadvisable for PM-2A						
External Heating		Inadvisable for PM-2A						
Radiant Heating	A	A	A	A	A	A	A	A

On the basis of above tabulation the Radiant Heating is selected for further study.

5.0 DISCUSSION OF RADIANT HEATING

The construction of the PM-2A reactor vessel is such that the thermal shield in the vessel may be removed. By replacing the thermal shield with a heater assembly of approximately the same geometry, there is no need to drain the water in the upper shield tank. Thus, the shielding integrity of the upper shield tank can be maintained. Also, with this arrangement it is not necessary to remove the core structure and control rods. It would have been necessary to remove them if the heating unit had been placed inside the thermal shield as proposed for the SM-1.

The heater assembly incorporates means for indication and control of temperature distribution during annealing. In addition, direct reading of the reactor flange temperature is provided to insure that sufficient annealing temperature has been attained.

The radiant heating method of annealing the PM-2A reactor vessel appears to be far superior to any of the other methods conceived, and it satisfies the criteria established.

Figure 5. Conceptual Design of Heater and Mock-up of Pressure Vessel for Heat Distribution Test

6.0 CONCEPTUAL DESIGN OF HEATER AND MOCKUP OF PRESSURE VESSEL FOR HEAT DISTRIBUTION TEST (FIG. 5)

The drawing shows the PM-2A vessel mockup with the heater assembly arranged for test to determine axial temperature distribution. The test is designed to provide adjustment of the heating elements until the desired temperature distribution is attained.

The heating assembly must be substantial construction because it is to be used not only for test but also for actual use in PM-2A during annealing. The heater parameters of concern are: the ID., the height, the locating means, the maximum OD and the handling tool. These parameters must be identical to those of the thermal shield. The heater structure is a hollow cylinder of stainless steel which acts as a reflector and carrier for the heating elements. A mechanism will be incorporated for use during annealing to measure and indicate remotely the temperature distribution of the vessel wall including the flange.

Figure 6. PM-2A Vessel Sketch

7.0 SKETCH OF PM-2A VESSEL

Figure 6 shows the PM-2A vessel details of interest in considering the annealing of the main barrel wall that is opposite the thermal shield. During annealing, the thermal shield will be replaced by a heater assembly of geometry within the outline of the thermal shield. The heater assembly will mock-up the means of alignment and will be designed to utilize the same handling tool as for the thermal shield.

For purposes of direct comparison between the vessel geometry and that of the main barrel mock-up, these sketches are drawn to the same scale.

Figure 7. Arrangement of PM-2A During Annealing

8.0 CALCULATIONS OF POWER REQUIREMENTS

Figure 7 shows the arrangement of PM-2A during annealing by radiant heating. The combined weight of the components shown is estimated to be 13,790 pounds. The thermal conductance of the insulated part of the vessel wall is:

$$U = \frac{1}{\frac{x}{K} + \frac{1}{C}} \quad \text{where } x = 2" \text{ glasswool, } K = .28 \text{ glasswool thermal conductivity} \\ \text{and } C = 1.5 \text{ airgap conductance (See Reference 4 - Page 170)}$$

$$= \frac{1}{\frac{2}{.28} + \frac{1}{1.5}} = .128 \text{ Btu/HR } ^\circ\text{F FT}^2$$

The heat transfer area with above "U" is:

$$\begin{aligned} \text{Barrel: } \pi Dh_1 &= \pi 46.75 \times 71" = 10,400 \text{ IN}^2 \\ \text{Bottom: } \pi D^2/2 &= \pi 46.75^2/2 = 3,430 \text{ IN}^2 \end{aligned} \quad 13,830 \text{ IN}^2$$

Heat loss through the insulated wall surface:

$$Q = UA \Delta T = .128 \times \frac{13830}{144} \times 620 = 7,650 \text{ Btu/HR}$$

The thermal conductance through flange surface:

$$h_c = 0.19 (\Delta t)^{1/3} \quad (\text{See Reference 4})$$

$$\text{Mean air temperature: } \frac{770 + 150}{2} = 460^\circ\text{F} \quad \Delta t = 770 - 460 = 310^\circ\text{F}$$

$$h_c = 0.19 (310)^{1/3} = 1.285 \text{ Btu/HR FT}^2 \text{ } ^\circ\text{F}$$

The heat transfer area with $U=1.285$

$$\begin{aligned} \text{Cylinder: } \pi Dh_3 &= \pi \times 42.75 \times 9 \text{ -----} = 1200 \\ \text{Ring: } .7854 (D+d) (D-d) &= .7854 \times 68 \times 12 = 640 \end{aligned} \quad 1840 \text{ IN}^2$$

Heat loss through flange:

$$Q = UA \Delta t = 1.285 \times \frac{1840}{144} \times 310 = 5100 \text{ Btu/HR}$$

Total heat loss at steady state: $7650 + 5100 = 12,750 \text{ Btu/HR}$

Thermal capacity: $WC\Delta t = 13,790 \times .133 \times 620 = 1,140,000 \text{ Btu}$

$$\frac{1,140,000 \text{ Btu}}{24 \text{ HR}} = 47,500 \text{ Btu/HR}$$

Power required for heater:

$47,500 \text{ Btu/HR} \times 2,928 \times 10^{-4} \text{ KW HR/Btu}$	---	$= 13.9 \text{ KW}$	(heatup 24 HR)
$12,750 \text{ Btu/HR} \times 2,928 \times 10^{-4} \text{ KW HR/Btu}$	---	$= \underline{3.7 \text{ KW}}$	(steady state loss)
Total		17.6 KW	

9.0 ANNEALING SCHEDULE

The time required for the entire reactor downtime is estimated to be:

	<u>Hours</u>
1. Reactor cooling down	48
2. Removal of dished shield tank cover	12
3. Removal of steam cover	6
4. Removal of reactor cover	12
5. Removal of fuel elements and control rods	24
6. Removal of thermal shield	12
7. Installation of Heater Assembly	12
8. Installation of new dished shield tank cover	12
9. Draining of vessel and primary system piping	24
10. Annealing cycle: Heat up-24 hours, Anneal-24 hours, Cooldown-24 hours	72
11. Refilling of primary system and the vessel	24
12. Removal of the dished cover	12
13. Removal of the Heater Assembly	12
14. Installation of the thermal shield	12
15. Installation of control rods and fuel elements	24
16. Installation of reactor cover	12
17. Installation of the steam cover	6
18. Installation of the dished cover	12
19. Start up reactor	<u>48</u>
TOTAL	396 Hours

If the annealing is done on an around the clock basis it will require
 $396/24 = \underline{16.5 \text{ days}}$.

10.0 CONCLUSION

1. Radiant heating was selected as the most feasible method of annealing the PM-2A pressure vessel in place, on the basis of the selection criteria. The heater assembly would replace the PM-2A reactor thermal shield.
2. Conceptual design of a heater assembly contained in a PM-2A reactor vessel mockup, representing actual PM-2A parameters was prepared.

If annealing is to be undertaken, the heater assembly must be thoroughly tested and adjusted in the mockup until the results of thermal distribution are fully reproducible. A reproducible correlation must exist between the temperatures indicated by the mockup vessel thermocouples and the control-thermocouples attached to the heater assembly. The temperature indications furnished by the control thermocouples will thus make it possible to monitor and adjust the temperatures at the vessel wall during annealing.

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