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SUPERHEATED STEAM ANNEALING OF PRESSURIZED WATER REACTOR VESSEL

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ABSTRACT
Thermal annealing of an embrittled Reactor Pressure Shell is the only recognized means for recovering material properties lost due to long-term exposure of the reactor walls to radiation. Reduced toughness of the material during operation is a major concern in evaluations of structural integrity of older reactors. Extensive studies performed within programs related to life extension of nuclear plants have confirmed that the thermal treatment of 850°F for 168 hours on irradiated material essentially recovers material properties lost due to neutron exposure. Dry and wet annealing methods have been considered. Wet annealing involves operating the reactor at near design temperatures and pressures. Since the temperature of wet annealing must be limited to vessel design temperature of 650°F, only partial recovery of the lost properties is achieved. Thus dry annealing was selected as an alternative for future development and industrial implementation to extend the safe life of reactors.

Dry thermal annealing consists of heating portions of the reactor vessel at a specific temperature for a given period of time using a high temperature heat source. The use of spent fuel assemblies, induction heating and resistance heating elements as well as the circulation of heated fluid were investigated as potential candidate methods. To date the use of resistance heating elements which are lowered into a dry empty reactor was considered to be the preferred method. Indepth research in the United States and practical applications of such a method in Russia have confirmed feasibility of the method.

The method of using circulating superheated steam to anneal the vessel at 850°F without complete removal of the reactor internals is described herein. After removing the reactor head and fuel, the core barrel along with the upper and lower core in PWRs is lifted to open an annular space between the reactor shell flange and the core barrel flange. The thermal shield can remain as originally assembled. Alternately, the core can be removed and substituted by a cylindrical skirt extending along the cylindrical part of the reactor shell. The reactor is then capped with a temporary enclosure including ejectors forcing steam into circulation inside the reactor along its walls.

The process is performed at ambient or low pressure. High velocity steam flowing in the range of 150 ft/sec in an annular space provides uniform conditions of heating the metal to be treated without significant thermal gradients. Hence the reactor can be brought to the required annealing temperature of 850°F within 24 to 48 hours. The circulation is maintained

by adding high energy steam which is only a small percentage of the steam in circulation. The balance of the steam is removed in external condensers.

The results of the thermohydraulic and stress analysis, as well as a description of the process and required fixtures are given. It is believed that the simplicity of the process and the marginal cost of the additional fixtures makes steam annealing a competitive candidate method to the currently considered process involving resistance heaters.

INTRODUCTION

The work performed by Electric Power Research Institute (EPRI) [1] has confirmed that holding the irradiated material for about 168h at a temperature of 850°F (454°C) results in 80 to 100% recovery of mechanical properties. The improvement of fracture toughness properties of ferritic materials of the reactor vessel during such anneal complies with requirements of 10CFR Part 50, Appendix 6. Moreover, as shown in Figure 1, for annealing at 850° the recovery is not sensitive to reirridation. Figure 1 defines the effect of reirridation on the Transition Temperature Shift for various annealing temperatures. For an 850°F anneal, the transition temperature shift during subsequent operation continues at the approximate rate which would have been expected if no anneal had been performed. The annealing method described herein is based on "dry" heating of the inner surface of the reactor using superheated steam circulating inside the reactor shell.

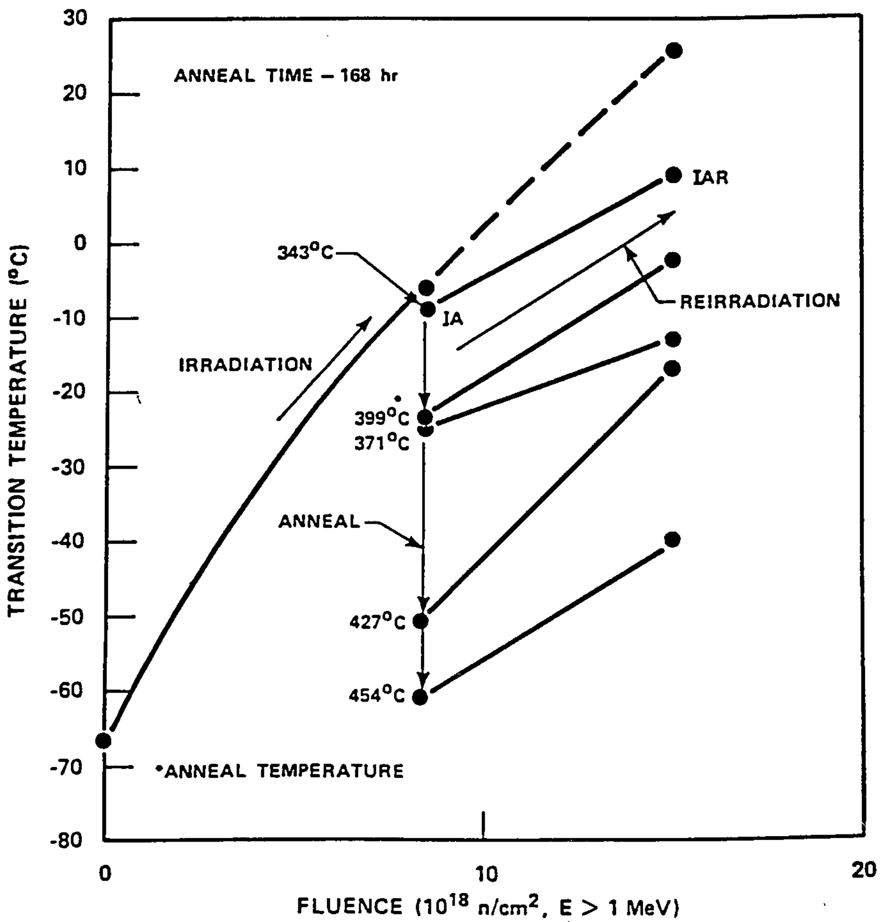

FIGURE 1 EFFECT OF REIRRADIATION ON THE TRANSITION TEMPERATURE

Complex geometry of the heavy wall reactor shell, including the upper flange and large diameter inlet and outlet nozzles, requires careful control of heat input to assure that the resulting thermally induced stresses remain within the allowed limits. The typical thermal transient rate during normal operation startup and shutdown of Reactor Pressure Vessel in Light Water Reactor nuclear plants falls within a range of 100°F/h. Raising temperature during anneal by about 800°F within a 24h period results in average thermal transient rate three times lower. Thus, for heating the entire inner surface of the annealed vessel, the stresses are about three times lower than during normal operating transient and therefore quite acceptable. The research work previously referred to [1] also confirmed that the thermal expansion of reactor piping and reactor supports can be accommodated without changes of existing systems. However, the feasibility of heating the shell should be verified on a case by case basis.

The stress limits are based on ASME Code allowables for secondary and peak stresses. Although the Code allows for raising the thermal stress range to 3 Sm, it is desirable that the heating and cooling rates required for the anneal are low enough to cause no plasticity except possibly for very local regions of high strain concentrations. For such regions, evaluation of the cumulative fatigue usage due to annealing, additional to the damage in the past and the continued expected life of the reactor, is required. As shown later by a finite element analysis, the stresses during heating and cooling remain within 15,000 psi. The largest stress occurs at the inner surface of the top flange. Such stresses are entirely acceptable per Code safety margins.

For the suggested steam anneal, the hot steam circulating at high velocity is in contact with the entire inner surface of the Reactor Pressure Vessel. The analogy of such heating to the heat transfer conditions during normal operation transients is much closer than in the case of using radiant heaters where only the belt region is heated. Radiant local heating causes discontinuity stresses in addition to the through-the-wall stresses. Since the proposed annealing is conducted at ambient pressure, the primary stresses have only a negligible effect on total stresses generated during the annealing process.

The analysis of the annealing process must demonstrate that the stress limits are also met in the case where the process is interrupted, or disturbed for example by failure of the local heat source. If the steam circulation is unexpectedly stopped, the temperature distribution in the shell material tends to converge to a stationary state with only small remaining stresses due to external losses of heat. The heating can be re-established without exceeding the maximum stress levels generated during an uninterrupted anneal. The steam heating system discussed herein eliminates the potential of local irregularities of heat supply. A situation resulting in significant stresses may occur if heat is supplied by radiant heaters with potential failure of individual heaters.

The process is based on using superheated steam as heating media in a closed fully sealed loop. Other gases can also be used. However, supplying energy to maintain inner circulation becomes less convenient. Steam ejectors proposed herein for the steam system are included into the loop inside the reactor. The use of the external fans for hot gas circulation required in case of noncondensable gases, although feasible, must involve the use of mechanical seals, which are not desirable for nuclear systems.

During the initial phase of heating, the steam can condense on the cold wall of the reactor shell. The condensate can either be drained and returned to the system as feedwater or can be removed by evaporation.

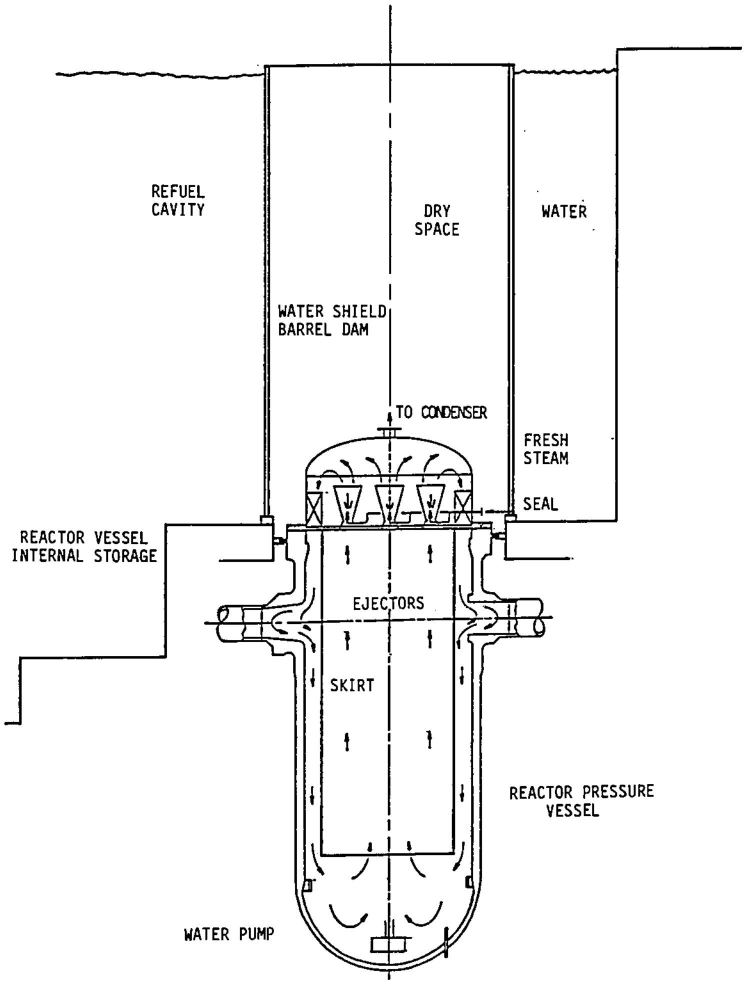

FIGURE 2 STEAM ANNEALING ASSEMBLY

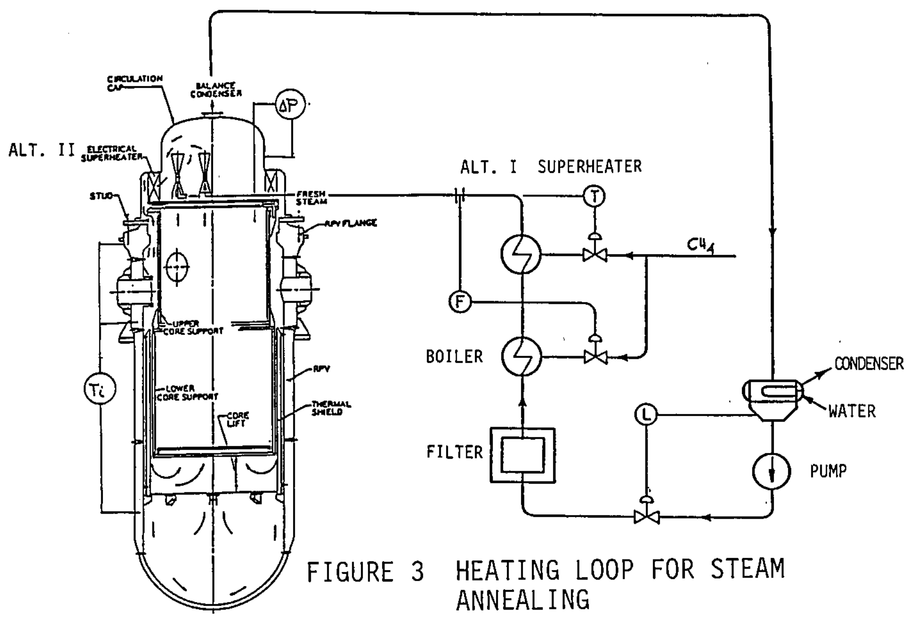

FIGURE 3 HEATING LOOP FOR STEAM ANNEALING

STEAM HEATING SYSTEM

The annealing is performed following removal of the fuel assemblies and reactor internals. After installing the water shield barrel dam and sealing it to the bottom of the fuel cavity, the water is pumped out of the vessel into storage in the refueling cavity analogously as described in [1] for radiant heating. The open top of the reactor is then closed by the additional fixture schematically shown in Figure 2. The fixture allows circulation of the steam along the inner surface of the reactor vessel. The energy needed to maintain flow of circulating steam in the annular space between the reactor wall and the skirt, is provided by the fresh steam used in ejectors installed at the top seal plate. The process is performed at ambient pressure. The velocity in the annular gap remains within a range of 150 feet/sec. Only a small temperature difference of about 20°F is required to supply a sufficient amount of heat to the reactor vessel shell. The process consumes about 2t/h of fresh stream at pressure within a range of 20 to 60 bars. Such a steam is provided from an auxiliary steam generator.

The schematic of the heating loop is shown in Figure 3. The balance of steam from the reactor is returned at low pressure to the condenser and is pumped back through a filter to the steam generator supplying the fresh steam to the ejectors. Annealing heat is provided by outer and inner heaters.

The schematic of the reactor included in Figure 3 shows the special case of the reactor, where due to lack of storage space in the pool, the inner and upper barrels cannot be removed from the reactor. Tight clearances within the upper flange regions, where the core barrels are supported, do not accommodate the thermal expansion at 850°F. Lifting of the upper and lower core barrels by about 2 feet eliminates the interference problem and opens the gap enabling steam circulation without using an additional inner skirt. The reactor sketch in Figure 3 shows the modified fixture for such reactor design alternative.

THERMAL AND STRESS ANALYSIS

The history of steam temperature at the inlet to the annular space is shown in Figure 4. A twenty-four hour heating period is followed by 168 hours residence time. Before reaching 212°F, the heating is accomplished by adding a small amount of steam condensing at the walls of the reactor. The pressure can be maintained by adding a small amount of neutral gas. At the end of the heating system and throughout the hold period, the steam temperature is raised slightly above 850°F to achieve and maintain the metal temperatures within 850° $\pm$ 10°F.

Figure 4 also shows the temperature response and the resulting maximum stresses at the inner and outer surfaces of the shell in the characteristic location of the shell. Reaching 850°F is only required in the critical beltline region of the reactor shell.

The plots shown in Figures 5 illustrate the temperature and stress distribution in the reactor shell at the end of the heat up period. The maximum stress occurring at the end of heat up transient is lower than 15,000 psi.

The process can also be completed by circulating air. At similar circulation rates and temperature history, the stresses should also remain within the allowable limits.

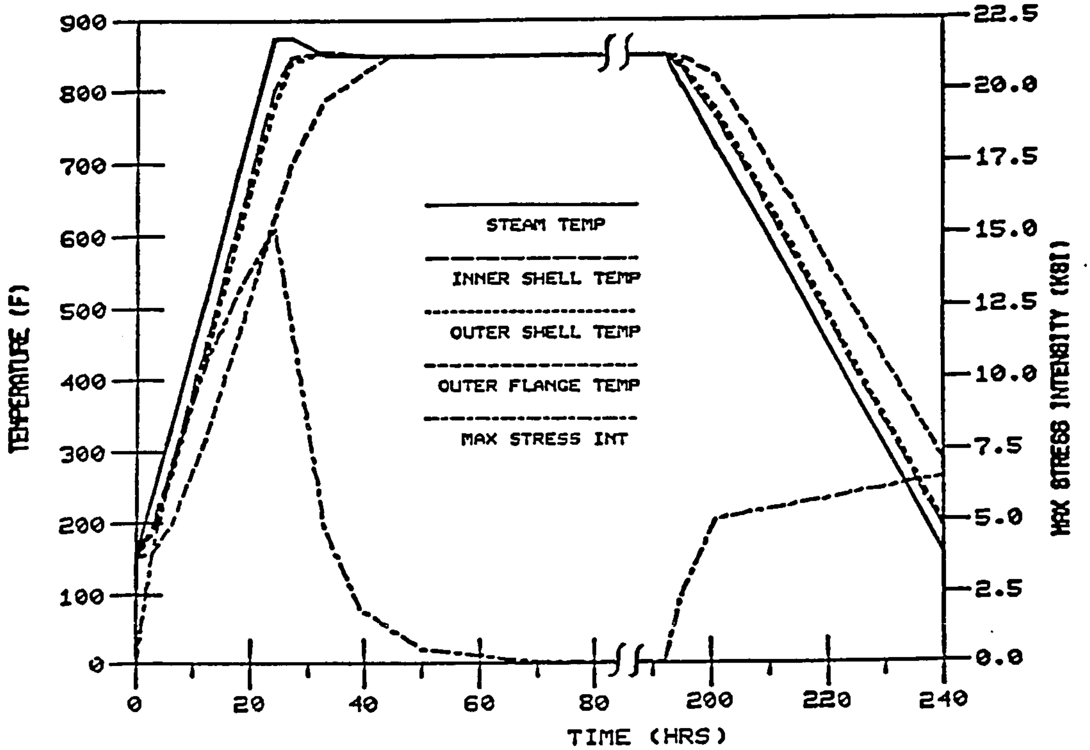

FIGURE 4 TEMPERATURE AND STRESSES DURING STEAM ANNEAL

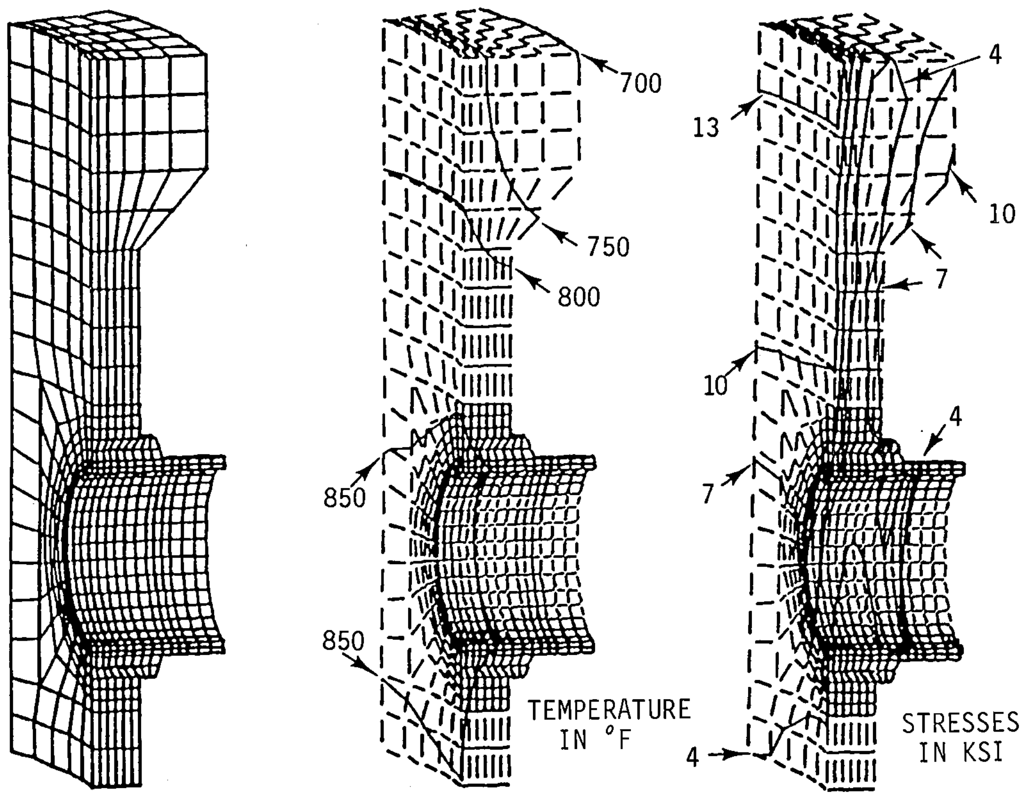

FIGURE 5 3D FINITE ELEMENT MODEL WITH TEMPERATURE AND STRESS PLOTS AT THE END OF HEATUP TRANSIENT

COST AND SCHEDULE

Preliminary evaluation of cost indicates that the process can be completed for significantly lower cost than the alternate with radiant heaters. The cost of fabricating and installation of the additional fixture and a water dam, as well as additional components of the heating loop, is estimated to be about $1.2 million. The cost of completing the annealing process should remain within a range of $3 to 6 million. The annealing process requires about two weeks. This time does not include removing of fuel and reactor internals.

CONCLUSIONS

Steam annealing represents an attractive alternative to the resistance heaters. Only a simple and fully sealed auxiliary system is required to complete the process.

The process provides very uniform heating conditions across the entire inner surface of the reactor vessel resulting only in small thermally induced stress. The process is very forgiving in that interrupted heating does nto increase stresses. Steam annealing can be used for reactors with or without internal and thermal shields.

The paper addresses specifically annealing of Pressurized Water Reactors. However, the method is applicable to all Light Water Reactors including Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs).

REFERENCES

[1] T. R. Mager, T. U. Marston, et al., "Feasibility of and Methodology for Thermal Annealing an Embrittled Reactor Vessel, EPRI Report NP-2712.

[2] In Place Thermal Annealing of Nuclear Reactor Pressure Vessels, NUREG/CR4212 EGG-MS-6708, 1985.

[3] U.S. Patent Application SN 866,412, "Apparatus for Annealing Walls of Nuclear Reactors."

ACKNOWLEDGEMENT

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