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Main Heat Exchangers and Possible Protective Measures

TO: Distribution

FROM: Roy C. Robertson

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2Summary

If temperature gradients in the order of 200°F to 300°F exist across the heat exchanger shell, the total stresses in the walls may exceed the elastic limit of the material. Stressing beyond this point could cause undesirable residual stresses and perhaps serious deformation of the vessel. Leakage tests on the heat exchangers indicate a sensitivity to thermal cycling, therefore rapid and large changes of temperature probably would damage the leak tightness of the tube sheet. Effects of sudden temperature changes on reactivity are not in the scope of this memo.

Possible causes of rapid temperature changes in an exchanger, in decreasing order of severity, are: admission of relatively cool water to hot heat exchanger; admission of steam to cool exchanger; sudden loss of steam pressure in the vessel.

The chances of sudden cooling of an exchanger by accidental starting of a feedwater pump are somewhat reduced in the present design by a control interlock which should prevent starting of either feedwater pump unless the feedwater spreader pipes in both exchangers are covered with water. It appears feasible to warm up the exchangers with this protective water covering the lower half of the tube bundle. If three to four hours warm-up time is allowed it should be possible to collect enough condensate from the warm-up steam to fill to the 11" level required to start the feedwater pumps. Use of feedwater heaters (including mixing jets) gives limited protection because of the need for quick and sure response and because the heater installation itself is subject to improper operation. There is concern for the five to eight gallons room-temperature water in the feedwater lines if the exchangers are hot and without a protective layer of water.

A control could be installed to sense rapid temperature changes in the exchangers and to close the control valves in the feed, drain and steam

lines, and thus give a measure of protection against sudden admission of cool water, hot steam, or long blowdown.

Stresses Due to Sudden Heating or Cooling

The fuel and blanket system main heat exchangers have wall thicknesses of 1-7/8" in the cylindrical portions; temperature gradients set up across the walls by rapid cooling or heating cause stresses due to the differential expansion inside and outside that are additive to the circumferential pressure stress. Stressing beyond the elastic limit, or yield point, of the steel will cause residual stresses and perhaps some deformation of the vessel, although the latter is usually associated with cycling and temperature gradients of long duration. Perhaps the most serious consequence of deformation of the exchangers would be the additional stresses imposed on the high-pressure steam piping if the exchanger nozzles were warped out of alignment.

Using Timoshenko's⁽¹⁾ relation for the thermal stresses in cylindrical shells with temperature gradient in the radial direction, at points large distances from the ends, thermal stresses for various gradients across the shell were estimated (See calculations Appendix A). The circumferential pressure stress in the exchanger walls is 2300 psi at 240 psig internal pressure and is 12,960 psi at 1350 psig internal pressure. These values were added to the thermal stresses in the following table:

Table I

Stresses Due to Temperature Gradient

Temp. Gradient	Thermal Stress	Total Stress	
		At 240 psig	At 1350 psig
100	12,930 psi	15,230 psi	25,900 psi
200	25,850 psi	28,150	38,800
300	38,800 psi	41,100	51,800

(1) Timoshenko, S., "Theory of Plates and Shells", McGraw-Hill, 1940, p. 422.

The above thermal stresses assume no deformation. If bending stresses also occur, Timoshenko states that stresses calculated from the above relation are low by 25%. Estimation of the stresses due to temperature gradients higher than 250°F to 300°F was not made because the total stress then exceeds the elastic limit where the modulus of elasticity is no longer constant and the usual relations no longer apply. Estimation of a temperature gradient that would stress the shells to the ultimate tensile strength would be only speculative, particularly since failure would occur at some stress raiser.

The heat exchangers are fabricated of firebox grade steel, SA-212 Grade B having a yield point of 38,000 psi and a tensile strength of 70,000 to 85,000 psi⁽²⁾. In the temperature range 0 to 600°F there is in effect little decrease in tensile strength; the yield point will decrease, being about 33,000 psi at 600°F.⁽³⁾ The Code allowable working stress for the material is 17,500 psi.⁽⁴⁾

An appreciation of the time-temperature relationships in sudden heating or cooling of the main heat exchangers can be gained from the transient heat conduction theories of McAdams.⁽⁵⁾ Assuming a slab of semi-infinite thickness, initially at 80°F, the outside surface would respond to 400°F and 580°F instantaneous inside surface temperatures as follows (See Appendix B for calculations):

Table II
Temperature Gradients vs Time in Exchanger Walls

Elapsed Time Minutes	Inside Surface at 400°F		Inside Surface at 580°F	
	Outside Surface	Radial Temp. Gradient	Outside Surface	Radial Temp. Gradient
0	80°F	320°F	80°F	500°F
1	135	265	165	415
2	163	237	210	370
3	218	182	295	285
4	237	163	325	255
5	256	144	355	225
10	298	102	420	160
15	317	83	450	130

(2) Am. Soc. for Testing Materials, Part I Ferrous Metals, 1952, p. 424.

(3) Tube Turns, Inc., "Piping Engineering, 2.01", 1947, p. 23.

(4) ASME Boiler and Pressure Vessel Code, 1952, Section VIII, p. 72.

(5) McAdams, Wm. H., "Heat Transmission" McGraw-Hill, 1954, p. 34.

Discounting that the inside surface would not come to the temperature of entering steam instantly on its admission, these values indicate that temperature gradients of over 200°F could exist for two or three minutes if 240 psig steam were suddenly admitted, and gradients of over 300°F could exist for sudden admission of 1350 psig steam.

From the preceding values it could be concluded that if building service steam at 240 psig were suddenly admitted to the exchangers the shells possibly could be stressed to the elastic limit and if steam from the package warmup boiler were admitted, the shells probably would be stressed to beyond the yield point.

If the exchanger shells were soaked to about 580°F temperature by warm-up boiler steam and suddenly cooled by admission of 210°F feedwater, there would not only be the thermal stresses due to temperature gradient along the bottom segment but also bending stresses due to deformation of the vessel. Numerical evaluation of the total stress in this somewhat complex situation did not seem required for this study in that the total thermal stresses due to the radial temperature gradient alone are sufficiently close to the yielding strength to indicate a definite safety hazard.

Sudden Cooling Due to Incoming Feedwater

As indicated in the preceding section of this memo, the admission of 210°F feedwater into the heat exchangers if they are drained of condensate and at the temperature of the warm-up steam, is undesirable. (A similar but less serious condition might exist if the package warm-up boiler fuel supply should be interrupted but its boiler feedpump continue to operate to pump water through the boiler coil and into the main heat exchangers).

If the main heat exchangers are filled to a level above the feedwater spreader pipes inside the exchangers (a depth of about 11") the shock of

incoming feedwater would be largely cushioned. The control system is presently designed with a low-level switch on each exchanger liquid level control to cut-off or prevent starting of both feedwater pumps should either of the levels be below the spreader pipes. This interlock should give considerable protection against premature starting of the feedpumps.

Each heat exchanger is estimated to require about 275 gal. to fill to 2" above centerline, about 240 gal. to fill just above the tube bundle, and about 125 gal. to fill just above the spreader pipes. When filled to just above these pipes (about 11" of water at the centerline) one-half of the tube bundle will be covered. Methods of securing the initial 11" of water in order to start the feedpumps are:

1. Filling to 11" level with cold water before warm-up is started.

This procedure gives good protection from sudden cooling due to startup of feedpumps without reliance on the controls system but offers a slight disadvantage insofar as protection from sudden admission of steam is concerned. During warm-up the soup will be continuously circulated through the tube bundle, entering through the top half. Condensate will drip from the upper half of the bundle, steam will be condensing on the surface of the water and the circulating soup will carry heat from the condensing steam into the water surrounding the lower half of the bundle, setting up some thermal circulation, all of which it is believed will provide satisfactorily even heating - providing that the warm-up is done slowly. The capacity of the warm-up boiler is such as to permit a 3-1/2-hr warm-up.⁽⁶⁾ Thermal stresses in the reactor pressure vessel due to rapid heating must also be avoided, with the minimum warm-up time estimated at about 3 hours.⁽⁷⁾

(6) Hill, J. W., "Requirements for HRT Aux. Steam Generator", ORNL CF-54-5-30.

(7) Aven, R. E., "Thermal Stresses in HRT Pressure Vessel", ORNL CF-55-2-128.

2. Collecting condensate from warm-up steam. This method places reliance on the pump interlocks until the exchangers are filled to about the 11" level by collection of condensate. Of the two sources of warm-up steam supply, that from the warm-up boiler is most limited. The package boiler has steaming capacity equivalent to formation of about 200 gal/hr of condensate. If a three to four hour warm-up time is used, there should be ample opportunity to collect at least 125 to 150 gal. in each heat exchanger.

3. Warm-up using steam-water mixture. The time required to collect condensate could be shortened somewhat by by-passing the steam separator on the package warm-up boiler to furnish steam containing 10 to 15% water. The steam line from the main heat exchangers to the steam drums extends into the steam drums about 1" so that it would be necessary to also close the condensate drain on the drum in order to accumulate enough water in the drum to overflow into the exchanger.

4. Auxiliary source of 400°F, 1500 psig water. If for special purposes it is necessary to warm-up the exchangers with the condensate draining, consideration could be given to a small auxiliary water heater and pump to be used for initial filling.

The first or second method of operation listed above seems adequate.

In addition to the protection against sudden cooling afforded by the interlocking controls on the feedwater pumps, heaters on the feedwater lines may also be considered. The major considerations in selecting a heating device for the feedwater lines are the heater's hot water storage capacity and its speed of response to sudden load.

The heating medium for the feedwater could be either building service steam at 240 psig (396°F) or steam from the warm-up boiler at about 1500 psig

(596°F). The steam capacity of the latter is limited to about 1500 lbs/hr. On a continuous basis a heater capable of heating the full feedwater pump capability of 72 gpm from 210°F to 400°F would require about 8,400 lbs/hr of 240 psig steam. About 3,850 lbs/hr of the 240 psig steam would be required to heat the normal rated pump output of 33 gpm.

Since the fuel and blanket system feedwater pumps are cross-connected a heating device would be needed on both feedwater lines to insure against possible by-passing of a heater.

Three methods of heating the feedwater could be considered:

1. Surface type heat exchanger. The spare tube bundle from the HRE can heat 34.8 gpm of 212°F water to 374°F using 3,571 lbs/hr of saturated steam at 240 psig, and is thus capable of heating the normal rated flow of the core system feedwater pump. ⁽⁸⁾ The hot water storage capacity is about 0.33 gal.
2. Contact, or mixing type. A 2000-psi-test pressure tank could be fitted with silent-type steam nozzles supplied with steam from the warm-up boiler. If this tank had a capacity of 100 gal. or over it would offer substantial protection, and by taking its steam directly from the warm-up steam line the water in the tank would be essentially at the same temperature as that inside the exchangers. This type of installation would be relatively expensive.
3. Steam-water mixing jets. These devices, such as injectors, ejectors, syphons, mixing valves, etc., have the advantage of lower first cost, little space requirement and quick response to load if started properly. They would necessarily be operated by high-pressure steam from the package boiler, and thus would not afford protection if the warm-up were done with building

(8) Van Winkle, R., "Use of the HRE Tube Bundle as Feedwater Heater for HRT", ORNL CF-54-12-173.

service steam and the package boiler were not fired. Practically all of these devices completely condense the actuating steam, as would be desirable in this application, and therefore use about 10 lbs of water per lb of steam and heat the water about 100°F. A very brief survey of the manufacturer's literature ⁽⁹⁾ indicates that 1500 psig, 210°F entering water with 350 to 400°F exit water may be a radical departure from the listed top working pressures of about 250 psig, 160°F entering water with 100°F temperature rise. The reliability of the mixing jet as a water heater in event of starting of the feedwater pumps would be contingent on the device's self-starting features, as well as whether the package boiler were fired and on the line.

For the feedwater heaters to give protection against sudden cooling of the exchangers a check system or control would be required that would give some assurance that the heaters were functioning properly, with supply steam turned on, package boiler fired, etc. Use of a temperature sensing control at the outlet of the heater to cutoff the feedwater pumps should the temperature fall below a safe value is of questionable value since the normal feedwater temperature is 210°F, requiring a change in set point for the control after the filling procedure is completed. With the exception of a high-pressure storage tank for hot water, there is some doubt as to the ability of a heater to pick up from no load fast enough to guarantee that the first discharge will be sufficiently heated.

There will be five to six gallons of room-temperature water in the feed line to the fuel heat exchanger and seven to eight gallons in the blanket exchanger line. If this amount of water flashed to steam on striking a dry heat exchanger at 580°F, the amount of heat absorbed is sufficient to lower 1/2" thickness of inside surface of the bottom one-fourth of the shell about

(9) Sarco Company, Inc.; Schutte and Koerting Company.

200°F. To purge these lines of water by allowing warm-up steam to flow backwards through them would require by-passing of the check valves - a practice not recommended. It would require a very careful manipulation of pressures to cause warm-up steam to flow forward through the water to heat it without slugging the water into the exchangers. Thus, either the lines should be drained or the entrapped water should be heated by sparging with warm-up steam as the exchangers are warmed up. Use of a feedwater heater does little to eliminate this problem since the heater would probably be located adjacent to the feedwater pumps. Maintaining a protective blanket of water in the bottom of the exchangers at all times would do a great deal toward counteracting the slugs of cold water when the pumps were started.

Sudden Heating by Steam

In the present design, opening of building steam supply valve 338A in combination with either of valves 319A or 319B being open, could admit steam to a main heat exchanger. If the exchangers were cold and the valves opened quickly, a temperature gradient of 200°F or more could possibly be created across the vessel walls, as discussed on page 5 of this memo. If valve 318A on the package warm-up boiler steam supply line were suddenly opened with the boiler "idling" (feedwater pump on, fuel valve open, ignition switch on), the quick response of the boiler to load (claimed by the manufacturer to be full steam capacity of 1600 lbs/hr in three to five minutes⁽¹⁰⁾), could impose temperature gradients possibly as high as 400°F on a cold heat exchanger.

Installation of valves smaller than the 2" ones referred to above is not considered a solution to this problem since the valves must be large

(10) Besler Corporation, Emeryville 8, California, "Instruction Book for Besler Model 55X Steam Generator - Oil Fired, Modulated Control".

enough to pass the requisite warm-up steam (estimated at about 800 lb/hr max) and thus could not prevent undesirable amounts to flow into a cold exchanger if accidentally opened. Control valves with very small hand-valved by-passes could be interlocked to prevent opening of the main steam supply valves unless the system were first warmed up. Warning signs on the valves or removable valve handles could be considered.

Sudden Loss of Steam Pressure

Loss of steam pressure could be caused by the lifting and sticking open of relief valves, prolonged opening of blowdown valves, sticking open of condensate traps if valves 375A or 378A were open, etc. An attempt to calculate the pressure bleed-down time and the resulting temperature gradients across the vessel walls did not seem warranted for this study, particularly in the light of the many possible combinations of line sizes and lengths that could be involved. The worst case would probably be if the exchanger were essentially dry and at a uniform 580°F temperature from warm-up steam, the warm-up boiler supply were cut off, and the exchangers were suddenly opened to atmospheric pressure. A temperature gradient of 200°F could conceivably be generated across the walls.

The exchangers are fitted with pressure relief valves set at 1500 psig on the steam space and valves set at 1350 psig on the blowdown lines. The warm-up boiler has a relief valve set at 1600 psig, but a pressure-switch on the fuel supply could be set to tend to maintain the warm-up steam pressure below 1350 psig to prevent popping off of the exchanger reliefs.

The relief valves for the exchangers should be tried and the pressure settings confirmed before installation. Blowdown valves and line shut-off valves 375A and 378A should be kept closed except when absolutely needed to

blowdown or drain condensate, and warning signs might be used to indicate that the blowdown valves 375B and 378B are to be left open only one minute or less. ("The amount and frequency of blowdown depends on service, steaming rate and quality of feedwater, and should be determined by chemical analysis. In the absence of analysis, blowdown at least one full opening and closing of the blowdown valve every 24 hours" (11)).

Safety Control Devices

Use of interlocking control on each possible source of mis-operation would lead to considerable complexity. The low-liquid-level interlock on the feedwater pumps included in the present design, however, is of value.

A type of control which offers some measure of protection against sudden admission of cold water or steam or the abrupt loss in steam pressure (except when relief valves stick open), could be temperature sensing elements inside the exchangers operating through transducers and a differential temperature-time controller to over-ride and shut off the control valves in the feedwater, condensate drain, and steam lines in event the exchanger temperature changed too rapidly - say faster than 3 or 4°F per minute. To assure protection at least two thermocouples would be needed, one in the upper steam space and one at the bottom near the feedwater inlet. The liquid-level calibrating probe consisting of 1/2" Sch. 80 pipe (12) entering from the top of the exchanger possibly could be used for installation of a thermocouple in a long thimble to sense the steam space temperature. A thermocouple could be installed in the feedwater connection nozzle to sense the bottom temperature. There would be some lag to this system, but it should offer some protection against high temperature gradients being set up in the vessel walls.

(11) ASME Suggested Rules for Care and Operation of Power Boilers, 1949, Par. C-76, p. 16.

(12) Foster-Wheeler Corp., Details of 5 Mw Steam Generator. H-37725-D, Detail "U".

Appendix A

Thermal Stresses Due to Temperature Gradient

According to Timoshenko⁽¹⁾ the thermal stresses in cylindrical shells with temperature gradient in the radial direction at points long distances from the ends, may be expressed as:

$$\sigma_x = \sigma_y = \frac{E\alpha (t_1 - t_2)}{2(1 - \nu)}$$

where:

σ = stress, psi

E = Young's modulus = $27.4 \text{ psi} \times 10^6$ for SA-212 steel

α = coefficient of expansion = 6.60×10^{-6} in/in-°F

ν = Poisson's ratio = 0.3

therefore:

$$\sigma = \frac{27.4 \times 10^6 \times 6.60 \times 10^{-6} \Delta t}{2(1 - 0.3)} = 129.3 \Delta t$$

Appendix B

Temperature Gradients

According to McAdams⁽⁵⁾ the temperature in a semi-infinite slab undergoing transient heat conduction may be investigated as a function of time, temperature and distance, as:

$$y = \frac{t_a - t}{t_a - t_b}$$

where:

y = unaccomplished temperature difference, °F

t_a = temperature hot side, °F

t_b = beginning temperature cold side, °F

t = transient temperature, °F

and:

$$z = \frac{x}{2\sqrt{\alpha\theta}}$$

where:

k = conductivity = 25.4 Btu-ft/hr-sq.ft-°F

ρ = density = 475 lb/cu.ft

c_p = specific heat = 0.117 Btu/lb-°F

x = thickness of material = 0.1666 ft

θ = time, hours

$$\alpha = \text{thermal diffusivity} = \frac{k}{\rho c_p} = \frac{25.4}{475 \times 0.117} = 0.4575 \text{ ft}^2/\text{hr}$$

For high values of steam film conductivity the ratio of k/hx may be taken as zero. From Fig. 3-2, p. 35, McAdams⁽⁵⁾ plotted values of y vs. z allow solution for various values of θ. Two values of t_a were investigated, 400°F and 580°F. See Table II, page 5 this memo.

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