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INVESTIGATION AND REPAIR OF BAFFLE PLATE
DAMAGE IN THE HFBR PRIMARY HEAT EXCHANGERS

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INTRODUCTION AND SUMMARY

The purpose of this report is to document information relating to the investigation and repair of the defects in the baffle plates of the HFBR primary heat exchangers. The defects were first discovered during an extended reactor shutdown which had been scheduled to permit inspection of several components in the primary piping system. This inspection was part of the search for the source of metallic chips that had been recovered from fuel elements during the past year.

It is useful at this point to describe the two primary exchangers in some detail. They are U-tube exchangers, mounted in the horizontal position and have a length and outside diameter of 27 ft. and 56 in. respectively. D_2O , the tube-side fluid, is cooled by cooling tower water, the shell-side fluid. As can be seen in Figs. 1 and 2, the D_2O enters each exchanger through the lower nozzle, passes through the U-tubes and leaves through the upper nozzle. The inlet and outlet nozzles fit into the end of the exchanger shell which has the hemispherical head. The baffle plate separates the inlet and outlet plenum regions in the hemispherical head and serves to prevent D_2O from bypassing the tubes. At rated flow, the pressure drop through the exchanger tubes is 10 psi and consequently the differential pressure across the baffle plate is also approximately 10 psi. Table 1 gives additional data on the exchangers.

The initial visual inspection of the plates during the extended shutdown showed weld cracks and missing weld material along the junction of the baffle plate and tube sheet. Further investigation, including dye penetrant testing, radiography and photography revealed the following:

1. In the B exchanger, the fillet weld around the periphery of the plate had cracked everywhere except at the corners of the plate where the tube-sheet meets the hemispherical head. In addition, several cracks were evident in the plate itself.
2. In the A exchanger, the fillet weld had cracked all along the plate to tube-sheet junction except in the vicinity of the corners of the plate. The weld at the junction between the head and plate was intact and there was no evidence of cracks in the plate.

3. There is more than enough missing weld material to account for the metallic chips that have been recovered. In addition, the weld material specified in the exchanger fabrication drawing, is the same as that determined by chemical analysis of one of the recovered chips.

Each baffle plate is subject to a static load, due to the differential pressure across the plate and to vibration which is induced by primary pump excitation. The evidence suggests that these two effects in combination with a poor plate to tube-sheet weld, resulted in failure of the plate by fatigue. Thermal stresses, caused by the difference in the D₂O temperatures in contact with the two exposed surfaces of the plate are not large enough to be significant.

Repair of the plate by rewelding the defective fillet welds was ruled out because of space limitations and the possibility of damaging some tube to tube-sheet joints. Instead a structure was designed to support and stiffen the plate. The structure is shown in Figures 3 and 4. The two vertical 1-1/4" diameter rods transmit the static load on the plate to the shell. These bars are welded to the shell and bolted to the plate. The stiffening members, which are bolted to and capture the plate, increase the natural frequency of the plate so as to minimize resonance with the driving frequency produced by the pump. The supporting structure in exchanger B is more elaborate than that in A because of the greater damage in B. Holes of 1/4" diameter were drilled at the tips of the cracks in the plate in exchanger B in order to prevent crack propagation.

Essentially all parts of the structure are type 316 stainless steel (0.06% max. carbon), a material which is compatible with primary D₂O and with other materials in the system. Recognized quality assurance procedures were employed in connection with materials, welder qualification, welding and weld inspection.

Although the proposed design is conservative, it was necessary to determine if continued deterioration of the baffle plate will lead to consequences that have not been foreseen in the HFBR Safety Analysis Report. One of the principal consequences is that a plate fragment will break loose and damage the thermowells in the primary piping causing a

loss of D_2O . Another result is that a plate fragment may cause blockage of flow to a fuel element and possibly fuel plate melting. Accidents of these types have been treated in the SAR and therefore do not constitute unreviewed hazards. Baffle plate failure may also cause a change in the D_2O flow rate and temperature. This accident is not serious enough to jeopardize reactor safety.

INVESTIGATION TO DETERMINE EXTENT OF DAMAGE

The baffle plate defects were initially observed on December 29, 1969 when the viewing ports on the D_2O side of the primary heat exchangers were opened for inspection. The defects that were noted first were the 3/16 in. fillet welds which join the baffle plate to the tube-sheet in the hemispherical head of each exchanger. Careful visual examination revealed the following:

Heat exchanger A - Cracks and broken pieces appeared in both of the fillet welds (top and bottom) that join the baffle plate to the tube-sheet. The plate had separated from these welds across the entire face of the tube-sheet except for about 6 in. at each end of the joint. In addition, the baffle plate was displaced about 1/16 in. at the center of its span across the tube-sheet face. The bottom fillet weld had remained attached to the tube-sheet and had parted from the plate (see Photograph 1-28-70).

Heat exchanger B - Cracks and numerous broken pieces of the fillet welds (top and bottom) that join the baffle plate to tube-sheet were evident. Segments of weld several inches in length were entirely missing. As in exchanger A, the plate had separated from the welds that joined it to the tube-sheet, except for about 6 in. at each end of the joint. The plate was displaced upward about 1/8 in. above the segments of the bottom fillet weld that had remained attached to the tube-sheet (see Photograph 1-38-70).

In addition to the fillet weld failures, cracks were evident in the baffle plate. The shape and location of the cracks are shown in Fig. 2 and in Photographs 1-7-70 and 1-47-70.

Following the visual inspection, radiography and dye penetrant tests were done to provide further information on the extent of damage. In exchanger B, radiographs were taken of the plate cracks and of the bottom fillet weld that joins the plate to the hemispherical head. It had been anticipated that these radiographs might be of questionable value here because of poor geometry and accessibility. When the initial results proved inconclusive, radiography was discontinued.

The dye penetrant test was made by applying the dye penetrant to the top and the developer to the bottom of the baffle plate. In exchanger A the results confirmed the failure of the fillet welds that join the baffle plate to tube sheet. There were no cracks evident in the plate and the plate to hemispherical head welds appeared to be in good condition.

In exchanger B the tests verified the failure of the fillet welds that join the baffle plate to tube-sheet and delineated the cracks in the plate (see photograph 1-47-70). The test also indicated that the fillet welds that join the plate to the hemispherical head had failed. These welds were still firmly attached to the hemispherical head but had separated from the plate along most of its length (see Photograph 1-12-70).

PROBABLE CAUSE OF FAILURE

The most probable cause of failure of the baffle plates is fatigue due to plate vibration superimposed on top of a high static load. It is apparent that the failure occurred initially in both the A and B heat exchangers along the fillet welds between the 3/8 in.-thick baffle plate and the tube-sheet. The failure in the A exchanger did not progress beyond that condition while in the B exchanger the cracks propagated into the plate itself and the peripheral fillet welds between the plate and the hemispherical head also cracked.

In the fabrication of the exchangers a 2-1/4" wide strip was first fillet welded to the tube-sheet cladding while the semicircular portion of the plate was welded into the hemispherical head. The head was then joined to the tube-sheet with a circumferential full penetration weld. The final weld in the baffle plate, a full-penetration butt weld between the strip and the semicircular plate was made through the nozzles in the head. There is some evidence of lack of fusion in the fillet weld between the strip and the tube-sheet. This weld bead was laid in rather lightly;

the welder apparently did not put much heat into the weld for fear of damaging the tube-sheet cladding and the tube to tube-sheet joints that are nearby.

A high static tensile load is developed in the plate due both to the fabrication procedure and the loading of approximately 10 psi on the plate during operation. This loading results from the pressure difference between inlet and outlet D₂O. It is possible that these loadings alone could lead to failure, however, this cannot be proven because of uncertainty regarding the strength of the fillet weld to the tube-sheet. In any event, a tensile stress near the yield point in the material (35,000 psi) could easily be developed. The fundamental natural frequency of the plate is about 60 cps and there are higher harmonics at which the plate could resonate that are near the 160 cps driving frequency produced by the centrifugal pump. The alternating stresses resulting from plate vibration applied on top of the high static loading apparently led to fatigue failures in the fillet weld along the tube-sheet that propagated to the extent observed in each of the exchangers. There is no simple explanation for the fact that the failure progressed further in the B exchanger than in the A unit other than the obvious one of variability in welding technique.

DESCRIPTION OF REPAIRS

Exchanger A

The baffle plate repair to the A exchanger, illustrated in Figure 3, involves providing adequate structural support to the edge of the plate adjacent to the tube sheet and increasing the natural resonant frequency of the plate to a level greater than 250 cps in order to avoid vibration fatigue problems. A pair of 1-1/4 x 3 in. 316 stainless steel bars, 37 in. long, are bolted to the top and bottom of the baffle plate parallel to and 4-1/2 in. away from the tube-sheet. The bars are bolted to the plate with two 1-1/4 in. diameter 316 stainless steel rods that extend downward through the lower plenum and are welded to the hemispherical head. The two rod to head welds are the only welds performed in the A exchanger repair. All internal joints are bolted and .072-in.-thick Belleville-type spring washers made of Inconel-X are provided under each nut. The

two bars that run parallel to the tube-sheet provide a stiff section which will minimize the deflection of this beam, thereby minimizing any bending moment applied to the support rods. The higher fluid pressure acts on the bottom of the plate placing the rods in tension. The rods are sized primarily to avoid vibration problems and turn out to be oversized for the tensile load that they must carry. For design purposes it was assumed that each rod carries 8,000 lb, which is one-half of the total load (pressure differential X area) acting on the plate. This assumption is conservative since the peripheral fillet welds between the plate and hemispherical head are still intact in the A exchanger and can carry a significant fraction of the load. There is about 2.46 in.² of shear area where the rod penetrates the head resulting in a shear stress of 3,250 psi at the design load. The hemispherical head is capable of carrying this additional load.

Extra stiffening bars are bolted to the top and bottom of baffle plate to complete a triangular grid structure. With this structure in place, the natural frequency of the largest remaining unsupported portion of the plate is about 300 cps. The structure is located well away from the peripheral welds in order to minimize any additional load that is imposed on these welds by either thermal effects or bolting.

Exchanger B

In this unit the failure is more extensive. In addition to the failure of the fillet weld along the tube-sheet, the peripheral weld between the plate and the head is cracked. In this case the repair must provide for complete support of the plate as well as an adjustment of the resonant frequency. Support along the tube-sheet is provided by a pair of 1-1/4 x 3 in. 316 stainless steel bars parallel to and 3-1/2 in. off the tube-sheet face. The bars are bolted to the plate with the 1-1/4 in. diameter support rods that are welded to the lower portion of the hemispherical head as in the A exchanger. Additional stiffening structure is provided and two other support points are provided near the mid portion of the peripheral weld. This support involves two horizontal 1-1/4 in. diameter pins that fit with .015 in. diametrical clearance into the stiffening structure. These rods act in shear and, as is the case in the A exchanger, each is oversized with respect to the load it must carry. The slip fit into the stiffening structure is provided in order

to avoid a condition where differential thermal effects in the structure could accumulate and strain the very short active length of the pins. The resonant frequency of the unsupported portion of the plate is about 300 cps. All four bolted joints include Inconel-X Belleville washers.

In order to prevent further propagation of the existing cracks in the baffle plate, 1/4 in. diameter holes are drilled at the crack tips.

Quality Assurance Procedures

1. Material: All plate and rod materials are type 316 stainless steel with less than .06% C. This alloy was selected because it is superior to type 304 in crevice corrosion. Since the repair will create many crevices in the threads and nuts and against plates, the better material was specified. The material was ordered to the following specifications: (Certified chemical analysis was obtained.)
 - a. Rod: ASTM A-276 (latest). The rods were not in the annealed condition and had a yield strength that ranged from 65,000 to 89,000 psi. A metallographic sample from each rod was checked for carbide sensitization. The results indicate slight cold working but no evidence of sensitization was found.
 - b. Plate: ASTM-A240 (latest). Annealed.
2. Welding: Inspection during welder qualification and final welding was done by the Inspection and Quality Control Section at BNL. The Metallurgy Division performed the metallographic examination and monitored all welding operations and inspections.
 - a. Welder Qualification: All welding was performed by qualified welders specially qualified for this repair. The welders were qualified on 5/8" thick type 304 plates using the tungsten inert gas shielded arc process in the overhead position. The qualifications were done under Section IX of the ASME Boiler and Pressure Vessel Code. The samples were cut for tensile tests, root, side, and face bend tests; and metallographic examination. In addition the test plates were radiographed. The quality standard setup for the examination was that any indication of lack of fusion or discontinuity, and any inclusions or porosity exceeding that allowed in the code (Q21B)

were causes for rejection.

A qualified welder was allowed to practice on a mocked up joint of the same geometry as the support rod to exchanger head. Before a welder was allowed to weld on the heat exchanger, he had to demonstrate that he could produce an acceptable joint in the overhead position. The submitted joint was dye checked, radiographed and cut for metallographic examination. The quality standard for acceptance is as stated above for the qualification test plate.

- b. Procedure: All welding was performed by the tungsten inert gas shielded arc process. The filler rod used was that of type 308. Backup gas was provided on the inside of the head. The weld joint design is shown in Fig. 5.
- c. Weld Inspection: The first two passes of all welds were checked with dye penetrant. Any indication of cracks, laps, pits, or porosity was ground out and repaired. After the first and second passes, the welds from the inside of the head were examined to be sure that the cover gas was adequate, that there was good penetration and that there was no indication of dirty weld or porosities before the welding was allowed to proceed. All completed welds were radiographed and dye checked at the inside of the head. Any indication of porosity or questionable spots as indicated by the dye check was ground out. These examinations show that there was some pull back at spots of the plate due to weld metal shrinkage. These spots were ground to give a smooth blending in of the weld metal and the head material. The acceptance standard for the welds were guided by Section VIII of the ASME Boiler and Pressure Vessel Code.

POSSIBLE CONSEQUENCES OF FAILURE OF BAFFLE PLATE

The proposed repairs were designed to insure that further deterioration of the baffle plate does not take place. However, the possibility of continuing failure cannot be completely discounted, so that it is only prudent

to consider the hazards as they affect reactor safety. These hazards relate to the breaking and detachment of a fragment of the plate itself rather than to the less significant loss of cracked weld material around the periphery of the plate.

Flow Effects

The detached plate fragment may cause a reduction in the total core flow by becoming jammed in the primary exchanger exit nozzle or in the piping between the exchanger and the reactor vessel. A flow reduction would be detected by the flow instrumentation and would cause automatic reactor shutdown if the scram point was reached. It is not possible to visualize a complete loss of flow situation because even in the remote circumstance of failure of the baffle plates in both exchangers with complete blockage in each line, the shutdown pump will cool the core.

If the detached fragment does not cause flow blockage, the flow will increase rather than decrease. This will occur because some flow will bypass the tubes in the exchanger, creating a reduced pressure loss across the exchanger and causing the primary pump to seek an operating point further out on the head-capacity curve. It has been estimated that the maximum possible increase in total primary flow, assuming complete bypassing of the exchanger, is about 5%. This flow increase is not hazardous.

Fuel Element Water Channel Blockage

A fragment of a baffle plate may be carried into the reactor vessel and fall on top of or into a fuel element. The design of the inlet end of the fuel element, with its triangular ears and lifting bail, is such that it is highly unlikely that a baffle plate fragment could completely block flow to an element. In this connection, calculations recently reported* have shown that it is necessary to reduce the flow velocity in both channels adjacent to the hottest fuel plate by a factor of more than 2 to cause burnout at the hottest point in that plate. In order to achieve more extensive burnout covering several fuel plates, where the average heat fluxes are about 1/3 of the peak value, it is required that the flow be reduced by substantially more than the factor of 2 cited above.

One of the accidents** treated in the SAR was a fuel element flow blockage situation involving the complete meltdown of an element. This accident is more severe than any one likely to result from a baffle plate

*Memo from P. Tichler, dated Nov. 24, 1969, entitled "Effect of Fuel Element Blockage on HFBR Core Thermal Analysis"

**BNL-7661, p. 14-10, Plugged Water Channels in Fuel Element

failure.

Water Temperature Effects

When the primary exchanger tubes are partially bypassed by flow through the opening in the baffle plate, the heat removal capability of the exchanger will be reduced and the primary water temperature will rise. If the opening is large enough, the performance of the exchanger will be reduced to a point where the water temperature at the core inlet will reach the setback level and the reactor will shutdown. No hazard is seen here.

Damage to Core Inlet Temperature Instrumentation

There are four temperature sensing elements for monitoring the core inlet D_2O temperature. Two of these, T1a-103 and T1a-104, are thermocouples located in the 18" outlet line from each exchanger. TRa-101 and XR-100 are resistance thermometers located in the 20" line to the reactor vessel and see a temperature dependent on the combined flow from each exchanger. The thermowells that contain these elements project into the piping and are therefore subject to possible damage by debris being carried by the flowing D_2O . If damage is sufficient to cause rupture, loss of D_2O from the primary system would result. This falls into the category of accidents that have been treated in the SAR.*

If thermowell failure occurs in conjunction with damage to the associated temperature sensing element, no additional hazards are introduced. The loss of D_2O will cause a reactor shutdown through instrumentation which is independent of the temperature elements.

On the other hand, it is conceivable that damage to a temperature element may occur without leakage of D_2O . The temperature instrument will respond with a sudden change in indication and there may or may not be a high temperature alarm depending on the mode of failure. However, until the fault is discovered, the core inlet temperature continues to be monitored by the undamaged temperature elements.

*BNL-7661, p. 14-12, Primary system rupture

TABLE 1 DATA ON THE PRIMARY HEAT EXCHANGERS

Manufacturer:	Southwestern Engineering Co.
Tube side fluid:	D ₂ O primary coolant
Shell side fluid:	Cooling tower water
Rated flow per shell:	
Tube side	9,000 gpm
Shell side	4,000 gpm
Design pressures:	
Tube side	300 psig
Shell side	150 psig
Design temperature:	160°F
Operating pressures:	
Tube side	250 psig
Shell side	45 psig
Pressure drop (rated flow):	
Tube side	10 psi
Shell side	12 psi
Operating temperature (rated flow):	
D ₂ O in	134°F
D ₂ O out	120°F
Cooling water in	85°F
Cooling water out	119°F
Velocity of D ₂ O in tubes (rated flow):	7.3 ft/sec
Heat transfer rate:	
Clean	526 Btu/hr-ft ² -°F
Service	256 Btu/hr-ft ² -°F
MTD (corrected):	23.6°F
Surface per shell:	11,330 ft ²
Rated heat exchanged per shell:	68,500,000 Btu/hr
Materials of construction:	
Tubes 3/4 in. OD x 16 B.W.G.	ASTM A-249, stainless steel, type 304, .06% max. carbon, seam welded
Channel head	ASTM A-240, stainless steel type 304, .06% max. carbon
Tube sheet (extended to serve as body flange)	1/4 in. stainless steel type 308 ELC cladding laid on 4-3/4 in. ASTM A-212B carbon steel
Shell	ASTM A-212B carbon steel
Number of U tubes per shell:	1350

Table 1 (cont'd.)

Number of active tubes:

EA-101A	1345
EA-101B	1348

Number of plugged tubes:

EA-101A	5
EA-101B	2

Closure design:

Channel to tube sheet	Welded
Tube to tube sheet	Rolled and seal welded
Shell to tube sheet	Bolted, with gasket
Inspection hole in shell	Bolted, with gasket

Code requirements:

TEMA-R for entire cooler;
ASME Unfired Pressure Vessel
Code, with Cases 1270N and
1273N, for tube side only

FIG. 1
 ISOMETRIC OF PRIMARY SYSTEM

FIG 3

DESIGN		CHECKED		APPROVED		DATE	
1/22/70		NOTED		1/11		1/11	
GMOONEY		GMOONEY		GMOONEY		GMOONEY	
BROOKHAVEN NATIONAL LABORATORY UPTON, N. Y. 11973							
HFBR A HEAT EXCHANGER DAFFLE PLATE REINFORCEMENT 135V BR13-0202-0-3A							

BR13-0201-6-2

NOTES

- 1-WELD ROD SHALL BE 308 STAINLESS STEEL
- 2-FIRST TWO PASSES OF WELD TO BE DYE PENETRANT INSPECTED
- 3-COMPLETED WELD TO BE RADIOGRAPHED, ACCEPTANCE STANDARD IS SECTION VIII OF THE ASME CODE
- 4-WELDER TO BE QUALIFIED TO SECTION IX OF THE ASME CODE

SECTION A-A

FIG.5

NO. REV.	AMCT. NO.	L.L.S. NO.	ORDER NO.	DEPT.	JOB NUMBER	USED ON DWE. NO.	NO. REV. AMT.
DES. & TOLERANCE 1-28-70 G MOONEY				BROOKHAVEN NATIONAL LABORATORY ASSOCIATED UNIVERSITIES, INC. UPTON, N. Y. 11973 HFDR HEAT EXCHANGERS SUPPORT ROD WELD DETAIL BR13-0201-6 -2 A			
DATE 1-28-70				MATERIAL 308			
DRAWN BY G MOONEY				CHECKED BY []			
DATE 1-28-70				WEIGHT []			
FRACTIONAL TOLERANCE []				FINISH []			
ORDER NO. []				DEPT. []			
NO. REV. []				AMCT. NO. []

"B" EXCHANGER
MIRROR VIEW OF CRACK - TOP OF BAFFLE

BAFFLE

HEMISPHERICAL HEAD

"B" EXCHANGER

TYPICAL BOTTOM FILLET WELD - BAFFLE TO HEAD

"A" EXCHANGER

TYPICAL TOP FILLET WELD - BAFFLE TO TUBE SHEET

"B" EXCHANGER

TYPICAL BOTTOM FILLET WELD - BAFFLE TO TUBE SHEET

"B" EXCHANGER

CRACK - BOTTOM OF BAFFLE