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CONVERSION TO SELF-SUPPORTED FUEL ELEMENTS

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F. J. MOLLERUS, JR.

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PROCESS TUBE EXPANSION - 105-C
CONVERSION TO SELF-SUPPORTED FUEL ELEMENTS

August 9, 1961

F. J. Mollerus, Jr.
Reactor Design Analysis

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PROCESS TUBE EXPANSION - 105-C
CONVERSION TO SELF-SUPPORTED FUEL ELEMENTS

INTRODUCTION

A method of reducing gas leakage and rear face maintenance is to fix the rear gunbarrel and process tube to the shield and eliminate the need for a rear expansion bellows. This arrangement is being considered as part of the C-reactor conversion to self-supported fuel element program.

The fixed rear gunbarrel will require that all hydraulic load and thermal expansion elongation of the tube be taken through the front bellows. In the event that tubes freeze in their channels, forces due to thermal expansion and hydraulic pressure will be transmitted to the rear shield if the tube and rear gunbarrel are fixed to the shield. Calculated maximum forces which can be transmitted to the shield are given in this report. The probability and amount of restraint which can occur in the tube are discussed. Finally, methods of insuring that the restraint does not cause excessive forces on the rear shield are discussed.

CONCLUSIONS AND RECOMMENDATIONS

Complete restraint of a tube in its channel does not appear probable since the high forces that have been calculated for this condition exceed even those found in the NPR tube insertion tests. Partial restraint that is produced by loss of tube clearance and stack distortion or a combination of both is the more probable condition which can overload the rear shield. The forces produced by partial restraint must be kept below 400 pounds per tube in order to protect the shield against overload.

A thorough analytical solution to the problem of tube restraint and shield loading is not possible due to the uncertainties of graphite contraction, process tube creep, etc. On the basis of limited data available from tests on other tubes and distortion geometries, the use of a fixed rear gunbarrel is feasible providing the following design and operational bases are used.

1. Initiate a design test to determine the axial forces necessary to move a tube in a channel distorted to the extent shown in Curve C of Figure 1. The test can be used to determine the maximum amount of distortion that can be tolerated without causing pushing forces greater than 400 pounds. The test should include several diametral clearances for the tube channel (for example - 0.015, 0.030, 0.045 inches) to determine minimum design channel clearance. In the event that test shows the maximum allowable distortion is less than Curve C, Figure 1, provisions should be made in the design of the rear hardware to install rear bellows when excessive distortion and tube restraint occurs.
2. Provide front and rear fringe overbore to prevent graphite growth and to provide extra clearance to allow for tube flexibility under the severe inlet and outlet distortion that may occur after 20 years of additional operation (See Curve C, Figure 1). As much overbore as possible should be provided for this purpose.

3. Periodically check the operating conditions after conversion to the new tubes by (a) observing the amount of change in expansion of the tube through motion of the front bellows, (b) traversing a top tube to find the depression of the stack, and (c) removal of a few tubes to check channel conditions.

These recommendations are based on the following considerations.

1. The 20-year distortion curve (Curve C of Figure 1) is based on present contraction rates of C-reactor extrapolated quite far into the future. Contraction may saturate below this time and reduce the ultimate amount of distortion.
2. A test conducted on a B-D-F tube under distortion similar to the projected C distortion, in the sense that radius of curvatures for both tubes are about equal (see Curves C and D, Figure 1) gives a breakaway force of 625 pounds and a sliding force of 345 pounds. Thus, there is some promise that rear shield force limits will not be exceeded until the maximum C-reactor distortion occurs.
3. The B-D-F test used a channel diametral clearance of 19 mils. A 25 mil diametral clearance for the C-reactor tube appears satisfactory, although the effects of varying this dimension should be checked in the design test recommended above. Also, additional clearance need not be provided for contraction of the tube channel, since the temperature distribution in the tube block (see Figure 3) should prevent contraction in the region of the tube channel. High temperature contraction in the filler bars caused distortion of the stack.

DISCUSSION

The calculated forces and expansions contained in this report are based on the following parameters.

Thermal expansion coefficient of zirconium	$3.6 \times 10^{-6} / ^\circ\text{F}$
Active zone length	24 feet
Inlet-outlet lengths	8 ft.-4 in.
Process tube O.D.	2.25 in. 2.75
Process tube I.D.	2.147 in. 2.65
Inlet water temperature	2 C
Outlet water temperature	
Average	95 C
Maximum	130 C
Front header pressure	400 psig
Reactor power level	2515 MW

Tube expansion caused by two effects must be considered; hydraulic pressure and thermal expansion.

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Hydraulic Pressure Effect

When a process tube is subjected to an upstream pressure, P_o , a downstream pressure, P_i , and a coolant flow, the tube will be loaded with an axial load equal to $P_o A_o$, where A_o is the net hydraulic force area = the inside cross sectional area of the process tube. This load is balanced by an equal and opposite downstream force equal to $P_i A_i$ plus the coolant flow frictional drag on the fuel and tubing. If the tube is not restrained from axial movement, the tube will expand towards its inlet due to the strain produced by the hydraulic load. (This expansion is 0.147 inches for 400 psig front header pressure.) The inlet bellows will absorb the motion without transmitting force to either the front or rear shield.

In the event that graphite contraction and distortion or corrosion buildup on the outside surface of the process tube restrains free axial inlet movement of the tube, the rear shield must begin to absorb the rear hydraulic load.

The worst case, of course, is when the graphite at the point of restraint will not move nor will the tube between the rear shield and the point of restraint elongate under the hydraulic load. In this case, the shield must carry the total hydraulic load (1450 pounds per tube at 400 psig front header pressure). This is the worst case since any movement of the graphite or elongation of the tube will relieve some or all of the load in the rear shield.

Also it should be noted that the graphite at the point of restraint will be loaded by the hydraulic pressure exerted on the inlet portion of the tube. This force will help to break up any points of localized tube seizure or freezing between the graphite and tube.

Thermal Expansion Effects

As in the case of the hydraulic pressure, unrestrained thermal expansion will not exert forces on the front or rear shields. The elongations or thermal expansion of the tube will be absorbed by expansion of the front bellows and relative motion between tube and graphite. The following unrestrained thermal expansion of the tubes have been calculated, based on a fixed connection at the rear shield.

1. At Process Tube Inlet, δ_1 ,
 - a. 95 C coolant outlet temperature 0.161 in.
 - b. 130 C coolant outlet temperature 0.218 in.
2. At the Center of Active Zone, δ_2 ,
 - a. 95 C coolant outlet temperature 0.128 in.
 - b. 130 C coolant outlet temperature 0.177 in.

In the event that the process tube expansion is completely restrained at a point in the active zone or gunbarrels, thrust forces will be exerted on the shield as well as the graphite or gunbarrel. In addition, the tube will be placed in compression.

The following forces and stresses have been calculated assuming that the restraint point is at the active zone center and that no deflection of the rear shield or graphite occurs.

1. Forces exerted on the rear shield and graphite at point of restraint.
 - a. 95 C coolant outlet temperature 2540 lbs.
 - b. 130 C coolant outlet temperature 3500 lbs.

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2. Compressive stress in process tube between rear shield and point of restraint.

a. 95 C coolant outlet temperature	7140 psi
b. 130 C coolant outlet temperature	9830 psi

The following forces and stresses have been calculated assuming that the restraint point is at the end of the inlet gunbarrel and that no deflection of the rear shield or gunbarrel occurs.

1. Force exerted on the rear shield and inlet gunbarrel.

a. 95 C coolant outlet temperature	2030 lbs.
b. 130 C coolant outlet temperature	2745 lbs.

2. Compressive stress on process tube between rear shield and point of restraint

a. 95 C coolant outlet temperature	5700 psi
b. 130 C coolant outlet temperature	7700 psi

Thus, under conditions of tube restraint at the center of the active zone, the rear shield can have a maximum combined thermal expansion and hydraulic pressure load of.

a. 95 C coolant outlet temperature	3990 lbs.
b. 130 C coolant outlet temperature	4950 lbs.

Restraint at the inlet gunbarrel can cause a maximum load on the rear shield of:

a. 95 C coolant outlet temperature	3480 lbs.
b. 130 C coolant outlet temperature	4195 lbs.

There are several points about the above forces which require discussion.

1. The forces are maximum since the force exerted on the rear shield will be relieved in proportion to the amount of deflection that will occur in the graphite and shield. Neither the shield or graphite are designed to deflect under axial tube loads, but there is indication that shield motion occurs in F reactor when there are stuck gunbarrels.⁽¹⁾
2. Total restraint of the process tube is highly unlikely since the cyclic nature of thermal expansion and the potentially high forces which can occur should prevent tube seizure.

The key to the problem of loading the rear shield is to predict the conditions which will cause enough partial restraint of the tube to over-load the shield. Two phenomenon must be examined; contraction of the graphite channel down on to the process tube and distortion of the stack which will cause excessive bending of the tube.

Total contraction of the graphite channel onto the process tube should not occur under C reactor conditions. This is because of the temperature distribution in the lattice, typical values of which are shown in Figure 3. The graphite immediately adjacent to the tube will be in the range of 200-300 C, the transition point between growth and contraction. The inner portion of the tube block will tend to grow or remain constant, while the outer portion of the block will contract since temperatures exceed 300 C. This can cause stresses in the tube block which affect tube block integrity (longitudinal cracking of tube blocks have been noted recently; differential growth and contraction rates in the block may be a cause), but clearance between the tube and graphite should not be greatly affected.

The distortion that can occur in the top tube row due to graphite contraction can be estimated from the equation for contraction in the graphite in the center of C reactor active zone.⁽²⁾

$$\% \text{ Contraction} = \frac{365 \text{ P Y E}}{1000 V_g} = 2.85\%$$

where

P = the power level, 2515 MW

Y = the years of operation, 20 yrs.

E = plant efficiency factor, 0.8

V_g = volume of graphite in the active zone, 20,660 ft³

= the contraction rate, 2.5% per 1000 MWD/ft³ of graphite

= ratio of flux in vertical center tier of graphite to average reactor flux = 1.61

Curve B of Figure 1 has been calculated using the above contraction rate over an active zone height of 385 inches, i.e., the top center of the reactor will depress 0.0285 x 385 = 11 inches in 20 years of additional reactor operation.

Figure 1 shows the estimated total distortion (Curve C) of a top row C reactor tube after 20 additional years operation at 2515 MW. Curve B was added to Curve A, a recent traverse of the existing distortion, to obtain Curve C. The total contraction curve assumes that the existing growth "humps" will be removed during retubing and that temperature control (overboring to maintain +200 C fringe temperatures) will prevent further growth and cause some contraction in the fringes.

The opinion of most persons working in the graphite field is that contraction will terminate after 2 to 5 percent total contraction has occurred.⁽⁶⁾ Therefore, the lower limit will give a smaller contraction value than calculated above. The calculated values are within the 2 to 5 percent range and since they are based on data obtained from C reactor operating experience, they should be used for design purposes.

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The C reactor zirconium tube has a small moment of inertia ($I = 0.21 \text{ in}^4$). Therefore, it will be quite flexible and should offer small resistance to bending in a distorted stack. Estimates of the forces necessary to cause axial motion of the tube in a distorted stack can be made by analyzing the results of tests made on other tubes and distortion configurations.

Figure 2 shows the forces necessary to insert an NPR tube into a highly distorted stack as determined by tests.⁽³⁾ Some quotations from Reference (3) will add to the information contained in Figure 2.

"With the 25-year deflection (shown in Figure 2) approximately 1000 pounds was the normal pushing force for the passage (of the tube) through the graphite with peaks up to 3000 pounds after entering the far gunbarrel. Entering the far gunbarrel required over 5000 pounds force. This was in all probability when the end of the tube caught on the end of the gunbarrel while the 3000 pound and 2600 pound peaks were (due to) the tube conforming to the gunbarrel.

"The process tube was left in the 25-year deflected condition for two months and then pushed back towards the front for about 1-1/2 inches. A force of about 1800 pounds was required to start it and then it moved under about 1000 pound force. In this movement the galling or scratching is negligible."

The moment of inertia of the NPR process tube is 2.87 in^4 . Since tube flexibility⁴ is inversely proportional to the moment of inertia, the C reactor tube ($I = 0.21 \text{ in}^4$) is about 13 times more flexible than the NPR tube. Now, consider only the forces required to hold a tube in a distorted shape.

The pushing force required to move the tube through a distortion is equal to the coefficient of friction between tube and graphite, f , times the summation of the distortion forces on the tube, F_1 , or

$$F_T = f \cdot \sum F_1$$

Now, the bending forces for a C reactor tube should be 1/13 the forces of the NPR tube in a channel of equal distortion. Therefore, the forces required to start a C reactor tube into motion (breakaway forces) should be $1800/13$ or 140 lbs, and to sustain motion, $1000/13$ or 80 lbs., in a channel with the same amount of distortion as shown in Figure 2.

A factor not considered above is the clearance between the tube and channel. If the clearance is small, the tube must rigidly conform to the distortion dictated by the condition of the graphite channel. The radius of curvature of the tube will be smaller for less clearance in a channel of equal distortion. Therefore, the bending and pushing forces for a smaller clearance will be larger.

A test⁽⁴⁾ has been on a B-D-F size zirconium tube in a channel with the distortion shown in Curve D, Figure 1. It was reported that a breakaway force of 625 pounds and a force of 345 pounds to sustain movement was required for this particular test. These forces are quite high when compared to the NPR tube tests. The reasons for this appear to be:

- a. The B-D-F distortion has much sharper bends compared to the NPR distortion. The force required to move a tube through a distortion is inversely proportional to the bend radius.
- b. The clearance between the tube and graphite in the B-D-F test was 0.019 inches; in the NPR test, it was ~ 0.500 inches. The small clearance in the B-D-F tests could be a factor in increasing the forces.

Comparing Curves C and D in Figure 1, the 20-year distortion curve is about as severe as the B-D-F case, in the sense that radii of curvature in both cases are about equal. Therefore, forces as high as those for the B-D-F case can be expected for the predicted C reactor distortion. Overboring the fringes of the tube channel to provide extra room at the sharp inlet and outlet distortions will help reduce the restraint on a tube. The tube will relax to a less distorted shape and restraint forces will be reduced.

A point that should be considered in regards to any test such as the NPR and B-D-F test is that the tubes in both cases were new and undistorted when inserted into the test channel. Therefore, full elastic deformation forces were incurred when axial motion was made. The in-pile tubes will be slowly distorted to the 20-year condition. Yielding of the tubes will occur; they will tend to take a permanent set conforming to the distortion. Forces necessary to hold the tube to the shape of the distortion will be relieved. Thus, restraining forces will be reduced. Therefore, any short term, out-of-pile test should give conservatively high restraining forces.

The NPR test data can lead to optimistic conclusions about the C reactor process tube, while the B-D-F test will give pessimistic conclusions. Drawing an analogy to the C tube from either case must be done with caution since different conditions exist in each test and both will differ from the C reactor case.

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These conditions which affect the pushing forces are the degree of distortion (bending radii) and tube clearances. In the final analysis, forces for the C tube will not be known with a great deal of assurance until tests under C reactor conditions have been conducted.

An analysis by Brockmeir⁽⁵⁾ shows that the rear shield is capable of taking an average axial tube thrust of 400 pounds per tube, for the full pile configuration. Concentrated loads from single tubes may increase to 4800 pounds provided the the average over any sections does not exceed 400 pounds, or that the high load tubes are not concentrated in a localized region (two tubes on the same row should not exert this high force). In any case, a limit of 400 pounds per tube should be used, since concentration of high force tubes can occur. Excessive distortion will start at the top center of the reactor. Thus, tubes in this region will be first to become restrained.

FJ Mollerus Jr.

Reactor Design Analysis
Process Design

FJ Mollerus, Jr:bk

Attachment

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