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K REACTOR MODERATOR DISTORTION STUDY

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K REACTOR MODERATOR DISTORTION STUDY

By

W. K. Alexander and A. Russell

June 22, 1964

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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K REACTOR MODERATOR DISTORTION STUDY

INTRODUCTION

Irradiation-induced moderator distortion has plagued the Hanford reactors from their earliest days until the present. The first manifestation of graphite distortion was in the form of expansion of the B, D and F stacks. It was found that expansion was very temperature-dependent and could be reversed by raising the graphite operating temperature.

The DR, H, C and K Reactors were designed with provisions to minimize, or accommodate expansion. It was not until after the K Reactors had been designed that graphite contraction was recognized as a threat to stack life. Under the present operating conditions, contraction is largely dependent upon neutron flux levels. To date, this study has been largely concerned with the K Reactors, since the vast bulk of the distortion data available is from the Ks.

It was discovered after about three years of operation of the K Reactors that the top center was settling, control rod and process tube channels were becoming distorted, the side reflectors were moving out toward the thermal shields at the bottom, and gross voids were forming just inside of the reflectors.

The possibility of pushing the reflectors back was investigated but was never attempted. Since the investigation during 1958-1959 did not determine why the moderator stack was behaving as it was, there was no logical basis for corrective action, and so the problem was more or less dropped until quite recently, when rod operation became a problem.

Along with the distortion problem, came the problem of 3X Ball loss. The last full-reactor ball drop in a K Reactor was during 1958 and there was a considerable number of balls which were not removed. The magnitude of the ball loss potential is one of the subjects of this study and has a vital bearing on any proposed corrective action.

This study not only attempts to explain the mechanisms by which the K Reactors arrived at their present state of distortion but also provides a basis for forecasting future distortion. An understanding of the nature and magnitude of the forces at work within the stacks will enhance the possibility of devising means of counteracting the present trends.

SUMMARY AND CONCLUSIONS

K-Reactor graphite dimensional data from a variety of measurements and observations in VSR, HCR, test hole and process tube channels have provided a definitive picture of localized and over-all stack distortion. One of the primary objectives of this study has been to analyze there data and formulate a mechanism of stack distortion

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to explain these observations and to approximate the forces associated with stack movement. It is concluded from this study that one of the major reasons for observed stack distortion is due to the effects of nonuniform shrinkage of the graphite blocks in the reflector and adjacent fringe zones.

During irradiation, the blocks in these flux zones become tapered. The nonuniform contraction of these graphite blocks is due to the marked neutron flux gradient at the sides of the reactor; the greater contraction occurring at the ends of the blocks exposed to the higher flux. As with any column in which there is greater shrinkage on one edge than the other, the column of graphite blocks which compose the reflector and adjacent fringe zone will tend to lean over toward the center of the stack as contraction proceeds. The tendency for the sides to lean is resisted by a similar column on the opposite side of the stack.

During the first several years of operation, the stresses which would have been generated in these side segments, had they been completely prevented from moving, would have caused block fracture. Observations, however, show that these leaning side columns slid out away from the main body of the stack until they were against the side thermal shields at the bottom of the reactor. This phenomenon is attributable to the monolithic nature of the side reflectors due to extensive graphite keying. Once contact was made with the thermal shields and no further movement was possible, stresses generated within the side segments as contraction continued could not be relieved by movement and are believed to have resulted in breakage of a key or keys in the reflector. Once key breakage occurred, the sides were free to lean in against the contracted graphite core. The core movement, however, was restrained by VSR keys connecting the core blocks with the noncontracting blocks of the top reflector. Calculations indicate that a force of some 10,000 pounds would have had to be resisted by the four keys surrounding each VSR channel to prevent the side segments from leaning against the core. They were unable to take this load and therefore failed. This resulted in the development of a slippage plane between the graphite layers which compose the core. It is this slippage plane near the top of the stack which has resulted in vertical safety rod entry problems.

Two major problem areas which have resulted from distortion of the K stacks are interference with VSR entry and the potential loss of 3X balls into separations which have been generated in the blocks composing the VSR channels. Projection of future stack distortion indicates that continued misalignment of graphite layers will result in additional rod entry problems and that approximately 20 VSRs per reactor would become inoperative by 1970 if no corrective action is taken. Distortion is presently sufficiently severe that at least several rods would now be out-of-service if it were not for periodic channel broaching. It is also expected that VSR channel separations will continue to become larger and increase the magnitude of the ball loss problem. It is estimated that a ball drop at the present time would result in approximately 300-400 pounds of balls being lost in the stack. Further, it is assumed that this number will double by 1970 when the stack contraction has doubled.

A number of implications are inferred by this study, as follows:

1. The VSR entry problem can be solved by broaching or some other form of channel clearing. Process tubes will be lost-from-service by this approach, but the number is not expected to exceed 50 tubes per reactor over the next 15 years. Tubes lost-from-service are expected to be confined to the top ten to 15 tube row

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2. Technical and economic considerations do not appear to justify major dollar expenditures to prevent the removal-from-service of a relatively small number of process tubes.
3. Loss of some process tubes seems inevitable regardless of the approach taken to solve the rod entry problem. The installation of VSR channel sleeves would result in an initial loss of about ten tubes. If periodic sleeve replacement was necessary, because of breakage by the high forces predicted in this report, additional channel drilling would likely result in the loss of more tubes, possibly approaching the 50-tube figure associated with broaching.
4. The economic penalties associated with a permanent loss of 3X balls in the K stack are believed to represent a potentially more severe problem than the problem of rod entry. A loss of 300-400 pounds of balls is estimated to cost in the order of several million dollars, over a period of ten years following the drop.^[11] These numbers would increase somewhat by 1970. Of probably greater significance is the likelihood that the reactor could not be restarted following a loss of approximately 1000-1200 pounds because of nuclear safety considerations. It is well to point out that the estimate of 300-400 pounds is based upon extrapolations of in-reactor channel size measurements and mockup tests and could easily be in error by a hundred pounds or so.
5. It is not implied that there is not a rod entry problem or that reactor operation can continue indefinitely with a continuously degenerating VSR system, however, there are presently demonstrated techniques for maintaining rod operability where no such method is presently available for preventing ball escape from the VSR channel.
6. VSR channel sleeves probably represent the greatest assurance for ball retention. Considerable sleeve damage could be sustained before they would not satisfactorily function as ball containers. However, sleeve material of sufficient strength to withstand the predicted forces may prove a more satisfactory solution.
7. The plugging of VSR channel separation with artificial filler material such as graphite paste or graphite balls, while perhaps not as satisfactory as total containment with channel sleeves, may be adequate provided some ball loss is acceptable. Adoption of this approach would be contingent upon satisfactory demonstration of plugging ability and would be even further enhanced with a significant reduction in the probability of a serious ball drop. The use of ceramic balls in connection with this approach should also be considered.
8. Some ball escape can be expected from nearly all VSR channels in the reactor, whereas, rod entry problems are expected to be confined primarily to the near and far side channels.

In conclusion, it appears that VSR channel broaching or other similar procedure for channel clearing represents a technically and economically feasible solution to the VSR entry problem at the K Reactors. The Ball 3X problem is potentially more serious and is deserving of primary attention.

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DISCUSSION

Present Stack Conditions

The stack measurement program outlined in References 1 and 2 has provided a very good picture of stack distortion at the present time, particularly at the K Reactors. This information was obtained largely by traverses of the VSR channels with the "total data probe" and by taking moving pictures through the borescope. The total data probe measures the location of each of the four VSR channel walls in each graphite layer. When these data are plotted, it is possible to determine the channel location, channel width and slippage between layers at any point in a VSR channel.

Vertical height traverses of HCR channels, test holes, and process tubes give information of vertical displacement at many points throughout the stack. Horizontal displacement measurements in these openings add data on horizontal shifting to that obtained by the total data traverses of the VSR channels.

By compiling, plotting and analyzing all of these data it has been possible to construct quite accurate and detailed pictures of the present stack condition. Before examining these in detail, it is advisable to look briefly at the relationship between flux and contraction. It is well established that reactor-grade graphite contracts when irradiated at temperatures above about 300 C. For practical purposes, it can be said that all of the graphite in the Ks is above this temperature and therefore it is all contracting. At the other areas, most of the moderator is above this temperature and contraction dominates. At the B, D and F Reactors, there is an appreciable amount of the graphite, particularly near the front face, that is still expanding.

Figures 3 and 4 are composite plots of neutron flux and top vertical contraction in the front-to-rear and side-to-side directions, respectively. It can be seen that the accumulated vertical contraction is directly proportional to the flux in both cases. It has also been established^[4] that the graphite blocks contract about twice as fast in the direction parallel to their extrusion axis as they do in the direction perpendicular to the extrusion axis.

Figure 5 is an isometric sketch showing how the exterior of the K-Reactor stacks has changed.

Figure 6 is a transverse section of a K Reactor, which illustrates how distortion has affected the interior. From these illustrations, it is possible to draw the following generalized conclusions:

1. The top reflector is subsiding as the active core below it contracts, but is not contracting itself.
2. The side reflector keys have sheared just below the top reflector and the sides are leaning-in against the central core.
3. The side reflectors are out against the thermal shields at the bottom.

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4. Gross voids have appeared just inside the side reflectors in the lower part of the stack where the reflectors are out against the thermal shields.
5. In the side-to-side direction, just under the top reflector, the graphite is moving toward the center due to horizontal contraction and the compressive force of the tipping reflectors. In the intermediate layers (50 to 80) contraction has opened gaps between blocks fairly uniformly because static loading is more nearly uniform and there are no exterior forces in action. Toward the bottom of the stack, graphite is pulling toward the center, because blocks are more or less "tied together" by friction during equilibrium operation when the dimensional changes are taking place. This adds to the size of the voids left when the reflectors moved out. As will be explained later, this is the result of varying static load across the base of the stack.
6. Little is known about the detailed behavior of the front and rear reflectors because of the difficulty of observing any motion they have gone through. Assuming that the traverses of VSRs 23 and 69 are indicative of what the reflectors have done, then it appears that they are out at the bottom and tipped in at the top, just as are the side reflectors.

Figures 7, 8, 9 and 10 are plots of the total data probe traverses of VSR channels 46KE, 49KE, 42KE, and 23KE, respectively. These plots show in detail the shape of the VSR channels illustrated in Figure 6. Of particular significance is the gross slip plane between layers 120 and 121 in channel 49KE. This condition is typical of all channels on the sides of the K Reactors and is presumed the direct result of the force applied by the leaning side reflector. At any point where the side-to-side width of the VSR channels has increased by more than $\frac{3}{8}$ of an inch, the possibility of ball loss must be considered. Ball loss potential will be discussed in more detail later.

Past Distortion History

This section of the report will deal with the chronological progress of stack distortion, at the K Reactors, from their startup until the present time. The collection of distortion data over this nine-year period has been rather sporadic, and added to the difficulty of piecing the story together so that all of the available data make sense. Soon after discovery of stack distortion at the Ks, in June 1958, an intensive data-collection program^[5] was started which defined the extent of the distortion at that time reasonably well. Unfortunately, this study did not lead to an answer as to why the stacks were becoming distorted and, in the absence of this vital conclusion, it was impossible to devise any meaningful counteraction.

Reference 5 reports all of the initial data taken and discusses several hypotheses, none of which adequately answered the baffling question of "why". Before launching into an analysis of the stack distortion, it is interesting to note that in the 1958 survey there was no indication of layer slippage just under the top reflector, which is so critical today. The only two significant manifestations of distortion at that time were the rather modest, about one-inch, vertical contraction of the stack and the unexplained rapid outward movement of the bottoms of the reflectors.

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For purposes of clarity, and to avoid confusion, the following development of the general mechanism of moderator distortion will be based on the K stacks. Later in this study, comparisons will be made between the Ks and the smaller reactors. Figure 11 depicts a transverse section through the center of a K stack as it appeared in 1958 when the initial investigation was made. The key points depicted here are: 1) The top center has subsided about one inch. 2) The side reflectors were out at the bottoms about three inches. 3) The outward movement of the reflector had resulted in voids between blocks just inside the reflector. 4) The VSR channels were spreading in the side-to-side direction in the area of the voids, but were in normal shape in the upper half.

The two key facts, which are the basis for the following explanation of the graphite distortion phenomenon, can now be stated and must be thoroughly understood to make the whole discourse meaningful. These two points are:

1. The horizontal front-to-rear keys in the reflectors prevent movement of any part of the reflector toward the center of the stack unless all of the reflector above the part tending to move in is carried in with it. Conversely, if any part of the reflector moves out toward the shields, all of the reflector below must move out also. In this respect, the side reflectors act as monolithic graphite columns. The keying also requires that the angle between the top reflector and the side reflectors always be 90 degrees. For example, if the top reflector tips down 2 degrees, the side reflectors must lean 2 degrees.
2. As the result of the extensive side-to-side flattening, the central portion of the stack remains level as it subsides and the total change in elevation occurs in the outer 135 inches of each side of the stack. Since these side segments contract on the inner side while the outer side does not, they tend to bow and tip toward center. The sides tip-in faster than the central core contracts which results in high forces between the two.

The two tenets stated above are basic and are developed in detail.

Figure 12 illustrates the keying arrangement in the side reflectors. (It is also similar in the front and rear reflectors.) First, it will be noted that if a block in the filler layer tends to move toward the center of the reactor, the key in its outer end will carry all the blocks in the tube layer above with it. The key in the eighth block in the tube layer will in turn carry the filler layer block above it in also, and so on up to the top of the stack. On the other hand, such inward movement of a filler layer block will not carry the tube layer blocks below it toward the center, since they are free to spread apart. It will be shown below that this arrangement has a profound affect on the over-all distortion pattern and, had the keying arrangement been reversed, the slip planes would not have been so pronounced at present.

Figure 13-A shows how the keys force the side reflector out at the bottom when the top reflector slopes toward the center. Figure 13-B illustrates what could happen if the keys were reversed. This illustration shows that if slippage were possible between layers, the top blocks could tilt and the reflectors could remain effectively vertical.

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Figure 14 is a plot showing the projected outward movement of the side reflectors as the top of the reactor settles. When the stacks were laid up, there was a nominal 25-mil clearance between the keys and the keyways. This allows 25-mils slippage between layers. Since this slippage may be accumulative over the 130 layers, it could become significant. This effect is shown in the broken curves of Figure 14. However, this 25-mil clearance may be eliminated by the difference between parallel and transverse contraction of the blocks. The higher contraction of the filler layer blocks in the lengthwise direction would tend to compress the tube layer blocks thereby eliminating the original clearances.

Figure 15 has been prepared to illustrate the effect of the tipping tendency of the side portions of the stack. By the simple method of moments, it is shown that the force (F) required to prevent the side segments from leaning in is equal to the total weight (W) of the segment multiplied by one half of the width (w) divided by the height (h), or in equation form:

$$F = \frac{Ww}{2h} .$$

The concept of dividing the stack into tipping segments (A) and nontipping segment (B), as in Figure 15, is useful in analyzing what causes distortion. However, in practice, it is probably an oversimplification. It is quite apparent that the segments cannot act independently because they are laced together by the blocks in the filler layers. This inter-leaving tends to shift some of the weight of the center segment to the other segments thereby increasing the tipping forces.

In the early days of reactor distortion, before the reflector keys ruptured, this tipping force could have been as high as 1800 pounds per front-to-rear inch of the tipping segment. It is a well-known fact, when dealing with forces on bodies, that a horizontal force applied at one point must be resisted by an equal and opposite horizontal force if the body is to remain in equilibrium. The only force available to resist this tipping force is the friction force between the segment and the cast iron base on which it rests. Calculations indicate that this horizontal force is not sufficient to cause slippage between the graphite and the base, if the usual coefficient of friction of 0.3 is used. However, there are indications that in practice 0.2 may be a more realistic coefficient of friction. At this lower figure, sliding will occur. Also, "thermal walking" which results from the differences between thermal expansion transverse and parallel to the block axis may facilitate movement.

Using Figure 15 as a reference, a stepwise pattern of stack distortion will be developed.

1. Effects of Initial Contraction

The very first effects of graphite contraction would be noticed as a slight subsidence of the top of the graphite. Any horizontal motions would be taken up in tightening of keys, taking up clearance between blocks, etc.

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2. Effects of Intermediate Contraction

Any further contraction would result in further subsidence of the top and the beginning of outward motion of the reflectors. The meager data available indicate that this stage of distortion resulted in an over-all stack shape as shown in Figure 11. Indications are that if "total data" traverses of the VSRs had been made then (1958-1959), in the upper portions of the channels, the graphite would have been moving out under the influence of the reflectors while toward the bottom, with the possible exception of the three outer channels on each side, it would have been moving inward as the stack contracted. When the side segments start to lean in against the center section of the stack, the inner bottom of these segments tends to lift off the base. Figure 16-A illustrates this action using a simple stack of blocks. It can be calculated that when a horizontal force (F_H) is applied to the upper left-hand corner of the stack, the force at left-hand corners of the blocks decreases uniformly until F_H is just sufficient to tip the stack. At this time, the force between the left-hand corners becomes zero at all levels and the column may tip at any point from the top block to the bottom. Figure 16-B shows the same stack of blocks except a dead weight has been added on top. It can now be calculated, and it has been demonstrated experimentally, that when F_H is sufficient to tip this column it will always tip on the base. Calculations further show that, at the time of tipping, the force between the left-hand corners of successive pairs of blocks becomes less from the top down, and is zero between the base and the left-hand corner of the bottom block. (It is assumed in both cases that friction prevents slippage between blocks.)

Applying this principal to the moderator stack, as represented in Figure 15, it becomes apparent that the static load is not uniform across the bottom. Under the central segment of the stack, where the layers are level in the side-to-side direction, the load is uniform and can be calculated to be 36.2#/in² maximum. Between this portion and the side segments the static load changes from maximum to zero. At the outside of the reflector it is extremely high, since as shown in Figure 16 the entire weight of the tipping segment (or stack) is borne on the lower right-hand corner. This picture is, of course, oversimplified but illustrates the basic principal that a monolithic column, such as the rigidly-keyed side reflector will tend to lean over when its inside edge shrinks more than its outside edge. Since the column is prevented from leaning in, because it is braced against a similar leaning column on the opposite side of the reactor, it has but two choices. It can either break internally, allowing the section above the break to pivot about the top layer and slide out slightly, and that section below the break to lean in against the contracted graphite core; or it can slide outward on its base. In-reactor observations show that it initially slid out on its base.

As the reflector moves out at the bottom, it, in effect, stretches the layers in the side-to-side direction. At the K Reactors, these layers are held together only by friction between blocks which is directly proportional to the static load. Like any other bodies under tension, the layers yield most where they

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are weakest. Hence, the pulling apart just inside of the reflector. This is the basic reason for the formation of the voids early in the life of the Ks. Toward the top of the stack, the variation in static loading becomes less and less and as the layers were stretched they yielded more uniformly. Also, the total stretch became less and less toward the top, being zero at layer 130.

3. Effect of Continued Contraction

It is estimated that by about 1960 the side reflectors had moved out far enough to contact the thermal shield and could go no further. This did not stop contraction and, as the center continued to subside, the side reflector continued to bow, but could neither move out at the bottom nor in at the top to accommodate further tilting of the blocks so something had to give!! If the keying in the reflector had been strong enough, the reflectors would have ended up holding the top of the stack and the top thermal shield from subsiding any further. However, it can be shown that the horizontal reflector keys are not strong enough to support this load and therefore break.

As soon as the reflector keys failed, the side segments below the top reflector were able to tip in against the center core. At KW Reactor, the data indicated that the reflector keys between layers 120 and 121 on the near side, and 110 and 111 on the far side, ruptured. At KE, it appears that it was the keys between 110 and 111 on the near side, and 119 and 120 on the far side. After these keys broke, the graphite above these elevations became "dead weight" similar to the top thermal shields. Figure 17 indicates the force and weight distribution possible under this condition. It can be seen that the greater the dead weight and the lower the point at which tipping is resisted, the higher will be the force required to prevent tipping. The most important aspect of this phenomenon is that when a key in the side reflector fails, the leaning reflector is no longer supported by the rigid top reflector, but is free to buckle and lean against the moderator graphite in the upper process tube rows. The upper moderator graphite, in turn, is prevented from moving horizontally by the VSR keys connecting it with the top reflector. Thus, the leaning reflector is, in effect, again supported by the top reflector via the VSR keys. The VSR keys which would be loaded in shear if the blocks were level, are in fact loaded as a continuous beam at 3.75-inch intervals because the blocks are not level but are sloping at an angle. The force required to break the VSR keys under this type of loading is estimated to be approximately 1,000 pounds per key or 4,000 pounds for the four keys surrounding a VSR channel. This value is well below the calculated load of approximately 10,000 pounds bearing on each set of four VSR keys. The result is key breakage and the development of a slip plane in the VSR channels. The closer the channel is to the outside of the stack, the greater will be the slippage.

At the present time, the six outer VSR channels at each of the K Reactors are either completely blocked or closed to the extent that rods cannot enter. In the next bank of rods the slippage is severe, about 2 inches, and in many cases requires broaching to permit rod entry.

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Figure 18 is a plot showing the interrelation of vertical and horizontal contraction and side tipping. Inspection of the plot shows that above about layer 84 the reflector lean is greater than the horizontal contraction. Below 84, the reverse is true and therefore below this layer the stack will contract horizontally faster than the side reflector will lean. Practically, this means that the reflector, or the tilting segment, will never be resisted by the core below layer 84. The plot indicates, for example, that the present 5-inch vertical contraction would cause approximately 9 inches of lean. Obviously, this is impossible. At the point where the reflector key is sheared, between layers 119 and 120 at KE, the lean would be about $7 \frac{3}{4}$ inches. Again, this appears to be impossible unless one remembers that the bottom has been forced out $3 \frac{7}{8}$ inches from its original position. When this is added to the estimated $2 \frac{1}{2}$ -inch horizontal contraction at layer 119, it totals $6 \frac{3}{8}$ inches, which indicates that the total strain at present is about $1 \frac{3}{8}$ inches.

As contraction continues, additional tilting will occur and forces will build up until a reflector key fractures at a lower elevation. For example, when the vertical contraction reaches 7 inches (late 1966), the tipping tendency at layer 119 will be about $10 \frac{3}{4}$ inches. The horizontal contraction will be about $3 \frac{1}{2}$ inches at this elevation. The strain would then be about $3 \frac{3}{8}$ inches which may be enough to stress the keys to their breaking point. The point at which the keys break next is unpredictable with any accuracy, but it would be expected to be several layers down.

After the second break in the reflector, there may be no further shift at the first slippage plane; instead, a second plane will be generated and will remain active until the process repeats itself and a third slippage plane is created.

Predicted Future Trends

It is expected that as the moderator continues to contract, the reflector and that graphite just inside the reflector will continue to tip in. Since the top reflector is not contracting, the net effect will be progressive, closing off the VSR channels. At the present time, it is estimated that the slippage rate between the top reflector and the core at the VSR 49 position (and other similar positions such as 40, 58, 43, 34, 52, etc.) is about $\frac{3}{8}$ to $\frac{1}{2}$ inch per year. This means that 49 KE, which will just barely pass a $2 \frac{1}{4}$ -inch rod now, might be completely closed within four to five years if nothing is done.

The following groups of VSR channels are expected to become sufficiently distorted over the next ten years that rod entry problems are anticipated.

VSR Channels 26, 34, 43, 52, 60, 32, 40, 49, 58, 66.	} Distortion is already sufficiently severe in most of these channels that some degree of broaching is needed to maintain rod operability.
---	--

VSR Channels 35, 44, 53, 39, 48, 57.	} Rod entry problems expected in two to three years.
---	--

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Rod entry problems may also be experienced in a few VSR channels in the front and rear rod banks over the next ten years, however, rod operability should be maintainable by broaching with no danger to process tubes.

As contraction continues, the center graphite will continue to subside and the vertical distortion of horizontal rod channels and process tubes will become steadily worse. Although problems will be encountered in both of these areas, it is expected that the VSR and Ball 3X problems will continue to be the most severe unless some successful solution is forthcoming.

Front-to-Rear Distortion

The preceding analysis has been based entirely on the data obtained at the Ks in the side-to-side direction. The data available on front-to-rear distortion indicate two significant facts:

1. The same basic stack distortion mechanisms are at work in the front-to-rear direction as in the side-to-side direction. There are certain differences resulting from differences in the stack layup and the flux pattern. For example, the stack is not interlaced in the front-to-rear direction like it is in the side-to-side direction because the filler blocks and the tube blocks lie side-by-side in the tube layer. This, in effect, makes eight vertical graphite slabs which are not tied to each other except by the process tubes. These columns are free to act independently of each other which allows a degree of flexibility not possible in the side-to-side direction. The front and rear reflectors are keyed in the same manner as the side reflectors, however, it has not been visually substantiated whether these keys have been broken. There are front-to-rear slip planes visible in the extreme front and rear VSR channels, but it is possible that these could develop, due to action of the individual columns mentioned above.
2. Distortion in the front-to-rear direction is inherently less critical than in the side-to-side direction, since there is no real limit to how much graphite can be removed from the front or back of the VSR channels. The process tubes are nominally 5.694 inches apart which establishes the upper limit on graphite removal to facilitate rod entry. No such limit exists in the front-to-rear direction.

Consequences of a Ball Drop

In addition to rod insertion difficulties caused by layer slippage, stack distortion has also resulted in separation of the graphite blocks which compose the VSR channels at the K Reactors. Such separations would permit escape of 3X balls out of the channel and into the stack. Side-to-side and front-to-rear separations are possible in both tube and filler layers and are shown in Figure 19. In a filler layer, side-to-side separations merely create a ledge on the tube layer below, but no balls escape from the channel. These balls presumably could be swept off the ledges with no detrimental effects. A front-to-rear separation in a filler layer, however, creates a gap and allows balls to escape from the channel and run in the side-to-side

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direction and probably could not be recovered. In a tube layer, the effects are reversed. Side-to-side separations result in permanent loss while front-to-rear separations do not.

A series of mockup tests were performed to determine the extent of ball escape out of a VSR channel and into separations of various sizes. This data, together with in-reactor measurements of channel separation, were used to estimate the quantity and location of balls which would be lost at the present distortion condition. These calculations indicate that approximately 1000 pounds of balls would be permanently lost in the stack if all 51 hoppers were dropped. Removal of the six outer ball hoppers, however, has reduced this quantity to approximately 300 pounds.

Figure 20 illustrates the approximate total quantity of balls calculated to be lost from each channel. While definition of the number of balls which would be lost in each layer of each channel is beyond the scope of this report, balls generally escape into tube layers in the near and far side channels and into filler layers in the front, center and rear channels. These calculations are based on composite information from both K Reactors (see Figures 1 and 2) and it should not be inferred that these are exact values or that channels in both reactors are identical. It should also be noted that a certain amount of extrapolation is required, since not all channels in both K Reactors have been measured and an in-reactor ball drop will be somewhat different than that observed in a mockup test. Thus, the 300-pound figure could be either high or low, but is estimated to be within 100 pounds.

One of the significant conclusions which can be drawn from Figure 20 is that while the rod entry problem is confined primarily to the near and far side channels, the ball loss problem encompasses most of the channels in the stack. Thus, any dual-purpose approach which attempts to correct both rod entry and ball loss (such as sleeving) would involve perhaps twice as many channels as correction of the rod entry problem alone.

The reactivity loss associated with a 300-pound ball drop is estimated to be about 8 mk and would require approximately 180 additional E-metal columns for compensating enrichment.^[6] Because of total control considerations, it would not be permissible to simply randomly charge enough enrichment to make-up for the reactivity loss, rather, it would be necessary to place the enrichment at or near the location of ball concentrations. This would likely involve considerable borescoping and/or rod calibration tests to determine ball locations.

Projection of future ball loss problems is difficult to predict and would depend largely on what corrective approach is taken. For purposes of discussion, these approaches are divided into three general categories: 1) do nothing; 2) periodically fill separation between VSR channel blocks by caulking, graphite balls or other filler material; and 3) contain balls with some type of channel sleeve. Prediction of how large a separation will open up, between which blocks, in which channel, and when represents a degree of refinement not presently possible. It is therefore assumed that the separations in the stack and, therefore, the number of balls lost in the "do nothing" case will be proportional to the stack contraction; i.e., approximately 600 pounds of balls would be lost when the stack contraction has

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doubled. This is estimated to be by 1970. Again, it must be emphasized that the quantity of balls is a best guess and could be greater or less. Filling up the separations between blocks by caulking or dropping graphite balls would theoretically work, but in practice would probably be only partially successful and would have to be repeated periodically as the separations continued to grow. The adoption of this approach would be contingent upon satisfactory demonstration of plugging ability and the degree of conservation one wishes to apply to the calculated number of balls lost. The sleeving approach appears to provide the greatest assurance of ball containment. Even though the stack forces in this report are calculated to be in excess of the breaking strength of a graphite sleeve, it is believed that considerable damage could be sustained by the sleeve before it would no longer satisfactorily function as a ball container. To be effective as a ball container, the liners would probably need to be full length and installed in nearly all channels.

The cost of a ball drop is considered to result from:

- 1) additional outage time to locate balls for proper enrichment placement,
- 2) loss in conversion ratio,
- 3) loss in flattening efficiency,
- 4) increased minimum downtime, and
- 5) increased E-metal usage.

A firm cost breakdown is not possible at the present time, however, extrapolation from the DR ball-drop incident and an estimate of one week of outage time to locate 3X balls after a drop in a K Reactor suggests that a cost in the order of two to three million dollars might be expected over a ten-year period, following a ball drop of 300 pounds. A period of ten years was arbitrarily chosen because of the long-term effects of residual poison in the stack. A ball drop of 600 pounds would approximately double the cost. Aside from the dollar cost alone, an important consequence of the ball-loss problem is that, at some point, the residual quantity of ball left in the stack would become so large that continued operation under the present nuclear safety criteria would not be possible. Studies are presently under way to determine this parameter, however, preliminary estimates indicate that a ball drop of 1000-1200 pounds would require sufficient enrichment that the reactor could not be restarted in accordance with present nuclear safety requirements.

Implications of Stack Distortion Study

1. The stack distortion problem, as it applies to VSRs and 3X balls, will continue to become progressively more severe. While saturation of graphite contraction will likely occur at some future date, extrapolation of high flux test reactor data suggests that this might not occur in the K Reactors until stack distortion has progressed to two-to-three times the present condition. The following table of projected distortion in several parts of the K stack is a measure of the rate at which distortion is progressing. Thus, a doubling of distortion would occur by about 1970, when the elevation of the top of the stack has decreased 11 inches from the original layup elevation.

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	Shrinkage at Reactor Top Center	Displacement of First Rod Bank; e.g., VSR 43	Displacement of Second Rod Bank; e.g., VSR 44	Displacement of Third Rod Bank; e.g., VSR 45
Displacement per year	0.91 in.	0.4-0.45 in.	0.25-0.30 in.	0.1-0.15 in.
Total Displacement:				
Present	5.5 in.	2.0 in.	1.3 in.	0.6 in.
1966	7.3	2.8	1.8	0.9
1968	9.1	3.7	2.4	1.2
1970	11.0	4.5	3.0	1.5
1972	12.8	5.4	3.5	1.7
1974	14.6	6.2	4.1	2.0

If no corrective action is taken to insure continuity of channel opening between slippage layers, VSRs would become inoperative at about the following rate:

<u>Time</u>	<u>Number of Rods Inoperative Per Reactor</u>
Present	0 (several rods would be out-of-service at present if it were not for broaching)
1965	4-6
1966	10-15
1968	15-20
1970	20

2. The 3X ball loss problem may already be critical, depending upon the accuracy of the estimated ball loss. The present "best guess" of 300 pounds is probably accurate within 100 pounds and it is assumed that this quantity will double when stack distortion has doubled if no corrective action is taken. Eventually some point will be reached when a ball drop could become so severe that it would not be practical to operate the reactor. Studies are presently under way to determine this parameter. It is estimated that the present quantity of 300 pounds will increase by approximately 50 pounds per year. A preliminary cost estimate of a ball drop, based on extrapolation from the DR experience, is:

<u>Year</u>	<u>Pounds of Balls Lost</u>	<u>Estimated Cost over a Ten-Year Period</u>	
		<u>Out-of-Pocket Cost for Enrichment and Splines</u>	<u>Lost Production</u>
Present	300	~ 2,000,000	~ 2,500,000
1965	350		
1966	400		
1968	500		
1970	600	~ 2,500,000	~ 3,500,000

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As seen in Figure 20, the ball loss problem is not confined to only those channels in which there are rod entry problems. All VSR channels examined to date in the K Reactors exhibit some degree of separation and the gaps will likely continue to become larger and involve more VSR channels.

3. VSR operability can be maintained by broaching or some other form of channel clearing. Process tubes will be lost-from-service as distortion continues, however, some tube loss seems inevitable regardless of what approach is taken to insure rod operability. If the broaching approach is taken, the number of tubes lost-from-service is not expected to exceed 50 over the next 15 years. If the channels are sleeved, approximately ten tubes would be lost initially. If the sleeves were able to resist the loads imposed on them as distortion continues, no additional tubes would be lost. If, however, periodic replacement of broken sleeves were required, additional channel drilling would likely result in loss of additional tubes. The number could eventually approach the 50-tube figure associated with broaching if the sleeve replacement frequency were high.

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5. To be effective as a solution to the rod operability problem, sleeves would have to maintain a reasonable degree of integrity. If periodic replacement is required because they cannot withstand the stack forces, then it is questionable whether they offer any advantage over broaching. If they are to be used to contain balls, they must be used in most of the VSR channels in the reactor.
6. Sleeves, whether metallic or nonmetallic, probably offer the greatest assurance of containing balls. Caulking or plugging the VSR channel gaps probably would not be as effective as sleeving, but may be adequate, providing some ball loss is acceptable.
7. A cooled metallic sleeve probably has the best chance of withstanding the high stack forces predicted in this report, particularly if combined with isolation of the side reflectors by pinning the side reflectors to the top reflector. If metallic sleeves are unable to restrain stack movement, sleeve collapse and sleeve cooling tube damage may result. It is also possible that more than ten tubes would be lost during installation of these stiffer, longer-length, metallic sleeves since a straighter VSR hole would be needed.

Distortion Status of Other Reactors

As mentioned earlier, the vast bulk of the data collected, as well as the thinking and analysis, has been in connection with the problem as it exists at the K Reactors. To date, total data traverses have been made of only four VSR channels at C Reactor and one at B Reactor.

At C Reactor, VSRs 38, 40 and 41 were traversed and borescoped. Figure 21 is a plot of the distortion found in VSR 41. Due to its position in the C rod pattern, it should be about the most-severely distorted channel in the C Reactor. Preliminary inspection of the limited data from C Reactor indicates that a somewhat different distortion mechanism may be operative than that predicted by this report for the K Reactors. There are several significant differences between the C and K stacks. First, the C stack is not as high as the K stacks, nor is it made from the same type of graphite. This means that, for the same unit contraction rate, the top will subside less (the ratio of height is actually 427:487). Second, there are no horizontal keys in the side reflectors at C. This allows the reflector to tip in at will at any place. Third, the VSR keying at C is much stronger (eight 1 1/2 x 1 1/2-inch keys versus four 1 1/4 x 1 1/4-inch) and the keys are so arranged that the stack is keyed together in the side-to-side direction and cannot spread without breaking either blocks or keys.

The apparent net effect of contraction under the above conditions is multiple slip planes below the top reflector instead of the single slip plane observed at the K Reactors. The C case appears to be preferable, since the magnitude of the slippage at any one plane is less than it would be if it had all occurred at one point. If this had occurred all at one point, rather than several, it would have closed off the channel similar to the outer channels at the Ks.

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Considerably more data are needed before it will be possible to complete the over-all picture of the C stack distortion.

Borescopic examinations of a few BDF-type VSR channels indicate very little evidence of interlayer slippage and one traverse of a channel at B further indicated that the channels are relatively straight. There was considerable breakage of the vertical liner blocks noticed at B and D but it is believed that this was not a direct result of stack distortion. The graphite contraction rates at the B, D and F Reactors is considerably less than what it is at the Ks and C. This probably is the biggest single reason for the small amount of distortion noted.

There are no data available on the condition of the DR and H VSR channels other than fragmentary information resulting from inspections made during the course of normal maintenance and operation.

Possible Courses of Action

The course of action now being followed to develop a remedy to the distortion problem is reviewed by Corlett in Reference 8. Many possible, or suggested possible, courses of action have been compiled by Munro in Reference 9. Briefly, the tentative plan calls for reaming out the most seriously distorted channels and inserting short (about 8-inch) polycrystalline graphite sleeves which it is hoped will prevent further interlayer slippage and also prevent ball loss in case of an accidental ball drop. This course of action is based on the presumption that such liners will be strong enough to resist further slippage. Cooley[10] has proposed a method for determining the magnitude of the forces to be resisted by the liners. Calculations based on his method indicate very low forces which the polycrystalline graphite liners should be able to withstand. While the forces predicted by Cooley are probably real and of the magnitude he predicts, it is the conclusion of this study that the tipping forces described herein are greater by perhaps a factor of ten and indeed are sufficient to crush the proposed graphite liners at the slip planes. This conclusion suggests several alternatives to the present graphite sleeving approach.

1. Use cooled metallic liners rather than graphite. These could be made with almost any degree of flexural strength to restrain the stack. Such liners would incur a neutron penalty because of their absorption characteristics. Also, in those channels where slippage is the more severe, it will be necessary to sacrifice some process tubes in order to get the channel straight enough to install metallic sleeves. Had they been installed before the reflector keys ruptured, it would have been relatively simple and subsequent slippage might have been prevented.
2. Install high-strength pins between the top reflector and the contracting core. These pins would stop further slippage between layers. It would be particularly desirable to pin the side reflectors to prevent them from tipping in against the active core. Pins could be installed in the side reflector for nominal cost, since they would cause insignificant neutron losses and could be installed

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without endangering process tubes. Since it is expected that it will be necessary to pin only the top portion of the stack, it should be possible to install pins within the tube pattern, without loss of a significant number of tubes, if care is taken in the drilling operation.

3. The ultimate solution may very well be a combination of the alternates discussed above. Much will depend on the need for retention of 3X balls. If pins are installed to prevent the reflectors from tipping in it then may be possible to use polycrystalline graphite sleeves for ball retention. Another possibility, if the ball problem is not severe, would be to pin the side reflectors and use part length cooled metallic sleeves to keep the channels straight near the top where the slippage is greatest.
4. The use of flat VSRs should be considered. A flat rod with a 1-inch x 3-inch cross section has about the same nuclear properties as the present 2 1/4-inch OD flexible rods. Since there is no limit to graphite removal in the front-to-rear direction, where process tubes do impose a side-to-side limit, it seems only logical to consider a flat rod.

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FIGURE 1

VSR CHANNELS EXAMINED - KE REACTOR

			NEAR					
		33	(42)	51				
	26	34	(43)	52	60			
21	27	35	(44)	53	61	67		
22	28	36	(45)	54	62	68		
FRONT	(23)	(29)	(37)	(46)	(55)	(63)	(69)	REAR
24	30	38	(47)	56	64	70		
25	31	39	(48)	57	65	71		
	32	40	(49)	58	66			
		41	(50)	59				
			FAR					

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FIGURE 2

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VSR CHANNELS EXAMINED - KW REACTOR

				NEAR			
			33	(42)	51		
		(26)	(34)	(43)	(52)	(60)	
	21	27	35	44	53	61	67
	22	28	36	45	54	62	68
FRONT	23	29	37	46	55	63	69
							REAR
	(24)	(30)	38	47	56	64	70
	25	31	39	48	(57)	65	71
		32	40	(49)	(58)	66	
			41	(50)	59		
				FAR			

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FIGURE 3 FRONT-TO-REAR FLOW & DISTORTION PROFILES

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FRONT

FIGURE 5

ISOMETRIC VIEW SHOWING GENERAL SHAPE DISMOUNT

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FIGURE 6

TRANSVERSE SECTION OF K STACK ILLUSTRATING EFFECTS
OF DISTORTION

Layer

130
120
110
100
90
80
70
60
50
40
30

FRONT

REAR

NEAR

FAR

Original Centerline

Dashed lines indicate original position of channel walls.

Original Centerline

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Layer
130

Section of Channel
Broached Out

120

FRONT

REAR

NEAR

FAR

110

100

90

80

70

60

50

40

30

Original Centerline

Dashed lines indicate
original position of
channel walls.

Original Centerline

FIGURE 8 - VSR CHANNEL #49-KE

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Layer

130

120

110

100

90

80

70

60

50

40

FRONT

REAR

NEAR

Original Centerline

Original Centerline

2'

1"

0

1"

2'

2'

1"

0

1"

2'

FIGURE 9

VSR CHANNEL #42-KE

Dashed lines indicate original position of channel walls.

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Layer
130

120

110

100

90

80

70

60

50

40

30

FRONT

REAR

NEAR

FAR

Original Centerline

Dashed lines indicate original
position of channel walls.

Original Centerline

FIGURE 10
VSR CHANNEL #23=KE

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FIGURE 11

TRANSVERSE SECTION OF K STACK IN 1958, ILLUSTRATING EXTENT OF DISTORTION AT THAT TIME.

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Layer

FIGURE 12

SIDE REFLECTOR KEYING ARRANGEMENT AT THE K REACTORS

Detail of K stack as laid-up. Note that it is impossible for any part of this stack to slide out (or to the right) on the part below it; e.g., filler layer 126 cannot move to the right without either breaking a key or carrying the first eight blocks of layer 125 with it. These blocks in turn carry the filler block in layer 124 out also, etc.

Also note that motion in the opposite direction would only result in gaps between the first and eighth blocks in the tube layers.

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FIGURE 13-A

EFFECT OF TILTING OF TOP LAYER. AS TOP LAYERS TILT, EACH SUCCEEDING LAYER IS CARRIED OUT SINCE THERE CAN BE NO SLIPPAGE BETWEEN LAYERS.

FIGURE 13-B

ILLUSTRATION OF HOW SIDE REFLECTORS COULD HAVE REMAINED VERTICAL IN SPITE OF TILTING IF THE REFLECTOR KEYING HAD BEEN REVERSED.

FIGURE 14

FIGURE 15

ILLUSTRATION OF SIDE TIPPING TENDENCY CAUSED BY AN UNEQUAL CONTRACTION IN SIDE TO SIDE DIRECTION.

- (1) The original shape of the stack is shown by the dashed lines.
- (2) The "A" segments contain the graphite which is contracting unevenly-- blocks tilt.
- (3) The "B" segment contains the graphite which is contracting uniformly-- blocks do not tilt.
- (4) As the inner faces of the "A" segments contract, the segments bow and tip in against the "B" segment, resulting in forces at the top inner corners of the "A" segment as indicated by the arrows.
- (5) Since the top of the "B" segment has not contracted, these forces can best be relieved by outward motion of the base of the "A" segments.
- (6) The tipping tendency of the "A" segments transfers their weight to the outer corners as indicated by the arrows.

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FIGURE 16-A

Forces between
blocks, assuming
all weight is
supported at corners.

FIGURE 16-B

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FIGURE 17

ILLUSTRATION OF POSSIBLE TIPPING FORCES AT THE PRESENT TIME.

Assumptions:

- (1) Top cast iron weighs $2.62\#/in^2$.
- (2) Top 10 layers weigh $2.39\#/in^2$.
- (3) Average weight below 121 = $.260\#/in^2$ /layer.
- (4) All blocks in the area bounded by ABCD are tapered and tilting.
- (5) Blocks in the area bounded by EADF are not tapered and are level.
- (6) The graphite in the area EAGH although not tapered or tilting is supported largely at point G because of the inter-leaving of the stack.
- (7) The graphite in the area HIF rests largely on the base and does not contribute to the tipping forces.
- (8) $F_H = F_F$.

Based on the above assumptions, the following forces are calculated:

$$F_H \approx 2000\#/front-to-back \text{ inch.}$$

$$F_V \approx 7800\#.$$

FIGURE 18

INTER-RELATION OF VERTICAL CONTRACTION, LEAN, AND HORIZONTAL CONTRACTION

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Front-to-Rear Separation
of Tube Layer

Original Layup of
Tube Layer

Side-to-Side Separation
of Tube Layer

Original Layup of Filler Layer

Side-to-Side Separation of Filler Layer

Front-to-Rear Separation of Filler Layer

FIGURE 19

SEPARATIONS OF VSR CHANNELS IN TUBE AND FILLER LAYERS

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Layer

FIGURE 21

VSR CHANNEL #41-C

Dashed lines indicate original position of
channel walls.

Dashed lines indicate original position of
channel walls.