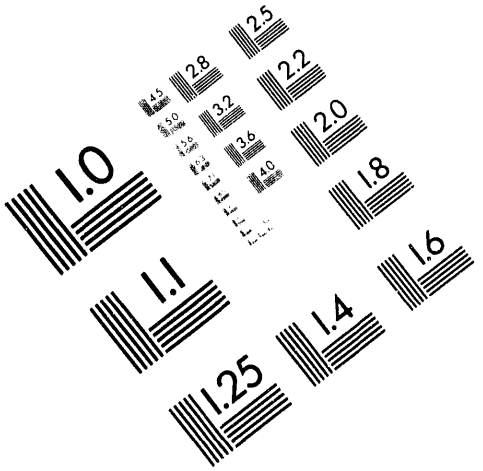

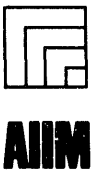

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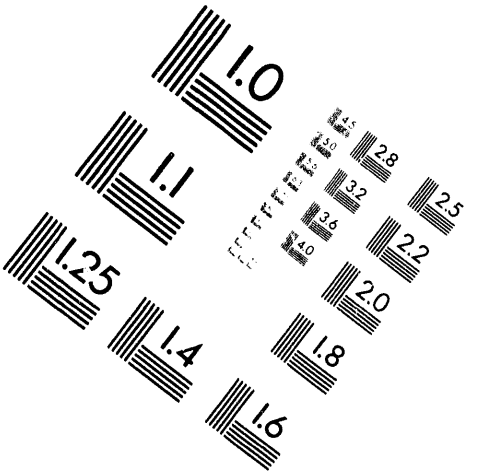

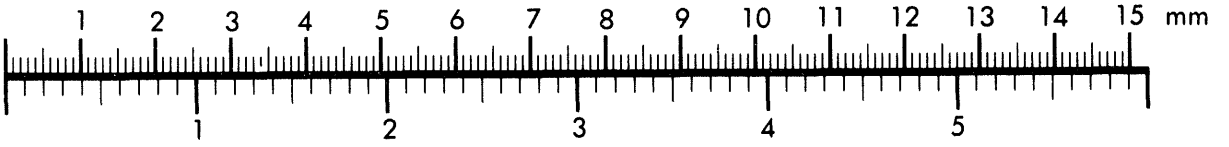

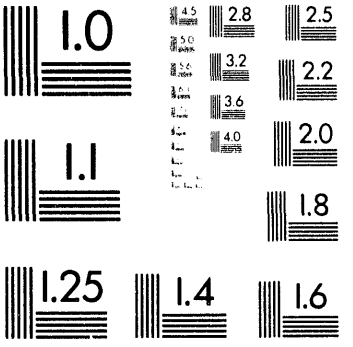

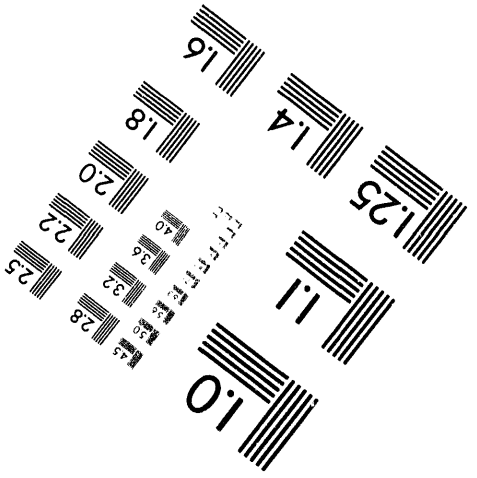

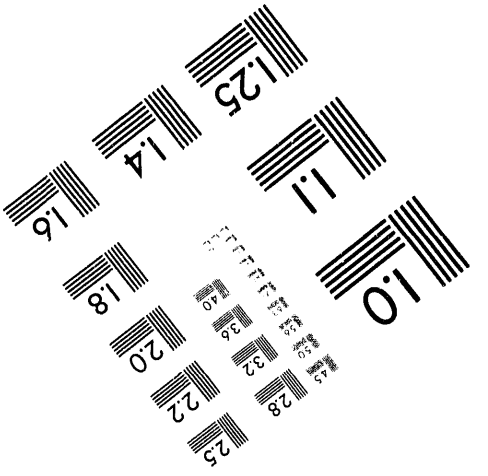

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DISCUSSION

PRELIMINARY REVIEW OF THE SAFETY ASPECTS OF THE CROSSUNDER LINE, PROJECT CG-884

by

S. S. Jones

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INTRODUCTION

In order to reduce both charge-discharge shutdown time and the number of manhours of radiation exposure, Project CGI-884 is being completed at the B, D, DR, F and H Reactors. This consists, essentially, of installing a large drain line at the bottom of one rear reactor riser. This drain line passes to a control valve and then to the effluent line beyond the downcomer. This system by-passes the crossover downcomer part of the effluent system and eliminates the need for intermittent rear crossheader valving during reactor charge-discharge procedures.

Two aspects of this system have been considered, its basic design requirements, and operating restrictions to ensure adequate process tube cooling. Because of the complexity of the reactor flow system approximate solutions were used to compare different methods or degrees of operation and establish limits. Despite these approximations, there was sufficient difference in the case results to justify the specific conclusions presented in this report.

This report should serve the dual purpose of providing design requirements for the crossunder and also providing the technical criteria necessary for the operating standards for the use of this new system.

SUMMARY AND CONCLUSIONS

Crossunder Design

Insofar as the design of this system is concerned the following conclusions are presented as leading to maximum system safety and reliability:

1. The crossunder line piping and close-off valve must be every bit as strong and reliable as the reactor rear riser system. To this end the close-off valve should be of steel, or well protected from shock loading, and the drain line* should be of steel with provision for corrosion inspection.

2. This drain line close-off valve should be operable from the 105 control room and, ideally, have the following limitations:

   a. Valve operation under lock and key control.
   b. Valve never to open unless front crossheaders are throttled to give a front-to-rear header pressure drop of 120 to 300 inches of water.**
   c. Valve to automatically close at TORPS ≤ 25 psig.

---

* The line from the riser to the close-off valve.

**Exception: at 20 hours or more after reactor shutdown (or equivalent heat output) the valve may be opened with crossheader valves throttled to give Δp values as low as 20 inches.

3. In the special case of the F-Reactor the above limitation on closing the crossunder valve imposes an additional requirement on the F crossunder system. Either the 1608 Building pump must be diesel powered or means of handling a storage basin overflow will be required.

4. Because water level backup in the drain riser with the crossunder open can cause flow loss in the lower reactor tubes it is necessary that a water level alarm be installed on the drain riser. This should cause a visual, audible alarm in the control room:

   a. Whenever the water level is higher than six inches below the bottom riser, and

   b. The crossunder valve is open.

5. A relatively large crossunder line capacity is desirable to handle available backup cooling. This crossunder line should have a minimum capacity of 10,000 gpm without causing a drain riser water level alarm. As reactor power levels are increased, this limited crossunder line capacity of 10,000 gpm capacity may extend the reactor shutdown time before this system can be used. Therefore, a capacity in excess of 15,000 gpm is desirable.

Crossunder Operation

The use of this crossunder system requires a number of changes in the present valving procedure to obtain adequate cooling of the reactor or adequate control of the cooling process. The general operating features consist of a drain line from the near riser with a close-off valve. The rear headers are valved to this riser by closing the crossheader valves leading to the far riser. The reactor flow to this drain riser is controlled partly by control of the top of front far riser pressure (TORP) and chiefly by throttling the flow from the front riser into the crossheaders. The safety limitations that should be imposed upon the operation of this system are listed below:

1. Going Onto the Crossunder System

   The major hazards associated with this system apply during the process of change-over from normal downcomer flow to that of throttled reactor flow through the crossunder. Therefore, it is essential that full backup flow and power be available during this transition period. To this end it is requested that transition to the crossunder be made only under the following conditions:

   a) Not less than four hours after reactor shutdown from equilibrium level and for any other shutdown the reactor heat output must have decayed to a level equivalent to 90 per cent of this four hour shutdown level.

b) Full BPA and steam pumping power must be available to the reactor's process pumps.

c) The export system and both high-tanks are available as a last-ditch backup.

In addition to these initial requirements the transition to crossunder flow should be made under the following limitations or procedures:

a) Four hours or more after reactor shutdown the reactor TORP should be adjusted to 80±5 psig (equivalent to approximately 28,000 gpm at the B, D, F and H Reactors), with the flow to the near front risers closed off.*

b) Maintain this 80±5 psig TORP while throttling the front far cross-header valves to a value of 140-300 inches of water Δp (header-to-header), throttling from the bottom header upwards.

c) Close all the rear far crossheader valves.**

d) Open the crossunder line valve and adjust the reactor TORP to a value of 60±5 psig by means of the process pump speed or pump discharge throttling.

e) Scan each crossheader as the flow is reduced and maintain tube outlet temperatures below 60°C.

f) Make a final adjustment of the crossheader throttle valves after the crossunder has opened and the level alarm indicates adequate drainage of the drain riser. The following restrictions apply to this procedure.

(1) Throttle in succession upwards from the bottom to give a 60 to 140 inches Δp header-to-header while carefully maintaining tube temperatures below 60°C.

(2) Not more than three of the crossheaders below row 23 may be left with the initial 140 to 300 inches Δp throttling.

(3) Not more than six of the crossheaders above row 23 may be left with the initial 140 to 300 inches Δp throttling.

(4) Not more than five central zone crossheaders to be left with the initial 140 to 300 inches Δp throttling.

---

* At the DR-Reactor the drain riser will be the rear-far rather than the rear-near riser. Consequently, the DR flow will be from the front-near to the rear-far riser during charge-discharge.

**The limiting p value to be controlled by the appropriate process standard, see page 3-3, HW-46000.

g) Supply process water with at least two 190 Building process pumps or five steam pumps and have at least the following emergency coolant backup:

TABLE I

BACKUP COOLING REQUIREMENTS

Time After Shutdown (hrs)	System	Required Backup	Remarks
0-4	Secondary Last Ditch	7-9 steam pumps* 2 hi-tanks and export*	No crossheader throttling
4-10	Secondary Last Ditch	3-5 steam pumps* 1 hi-tank and export	No crossheader throttling
4-10	Secondary Last Ditch	3-5 steam pumps* 2 hi-tanks and export	Crossheaders throttled and crossunder opened
10-20	Secondary Last Ditch	3-4 steam pumps* 1 hi-tank and export	
10-20	Secondary Last Ditch	3-4 steam pumps* 2 hi-tanks only	Export flow must be available within 2 hours.
20-48	Secondary Last Ditch	2-3 steam pumps* 1 hi-tank and export	
20-48	Secondary Last Ditch	2-3 steam pumps* 2 hi-tanks only	Export flow should be available within 10 hours provided front crossheaders are valved to yield max. allowable tube outlet temperatures.
2+ days	Secondary Last Ditch	2-3 steam pumps* Export	
2+ days	Secondary Last Ditch	2-3 steam pumps* 2 hi-tanks only	Export or equivalent flow of 500 gpm should be available within 20 hours.

*Whenever the 190 electric process pumps are neither supplying reactor flow nor on ready-standby the backup requirements of the table should be increased by one hi-tank or the export system whichever is applicable.

* EXPORT MUST BE AVAIL AUTO, OR BY MAN. OPEN OF IVALVE; OR Both high tanks

h) The location of the front and rear pressure taps has an effect upon the ratio of true to indicated Δp and flows for the different tubes along the header. Therefore, the following factors should be used in transposing the observed Δp values to minimum Δp and flow values along the header.

TABLE II

Reactor	Ratio: $\frac{\text{Minimum } \Delta p}{\text{Measured } \Delta p}$	Ratio: $\frac{\text{Minimum Flow}}{\text{Expected Flow}}$
C, DR, H	1.0	1.0
B, D, F	0.85	0.89

2. Shutdown Operation with Crossunder Open

a) Maintain tube outlet temperatures below 60°C.

b) Do not close the crossunder valve unless the number of end caps and/or pigtails removed per header is less than:*

1) Below row 23 - 5 per cent on any lower header,

2) Above row 23 - 10 per cent on any upper header.

3. Returning to Downcomer Flow

a) Put on all process tube end caps and pigtails that have been removed during the shutdown.

b) Close the crossunder line valve and lock in the closed position.

c) Completely open all throttled front crossheader valves in succession from the bottom upwards while maintaining a minimum TORP of 70±10 psig.

d) Completely open all the rear crossheader valves to the undrained riser.

Program

This is a preliminary report that serves to highlight the problems and suggest the safest means of operation. It is highly desirable that a program of the following nature be followed in order to supplement the data and theory now available.

* This does not contradict the 25 psig TORP automatic closing because TORP value should not reach 25 psig with proper throttling.

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1) Determine actual crossunder capacity and pressure flow conditions by means of suitable A.T.P. tests.

2) Make use of Washington State University flow analog to explore more thoroughly the flow problems presented by the use of this crossunder drain line with the multi-parallel path reactor system.

3) Apply the approximate methods developed in the appendices, towards a similar analysis of the C and K Reactor systems, and reapply this analysis at the old reactors after the completion of the crossunder line installation and testing.

DISCUSSION

1. Basic Hazard Considerations

The basic hazard of the crossunder line lies in the flow distortion that it can create with the possibility of insufficient flow to the top reactor tubes. This crossunder concept introduces the potential for reactor drainage in contrast to the submerged reactor concept created by the crossover downcomer piping system. The use of this crossunder system, however, under the incentive of increased production and reduced charge-discharge costs is acceptable provided certain basic criteria are met. These are listed as follows:

a. The introduction of the crossunder line and drain valve must not introduce any appreciably greater potential for reactor drainage.

b. The system must be operated in such a manner that flow distortions, sufficient to cause boiling and fuel column meltdown, are avoided both under normal shutdown and emergency shutdown conditions.

The operating limitations presented for the use of this system are more complete than for present operation. Thus, the new system used within the noted limitations should be safer than present operation.

2. Crossunder Line Piping

a. Water Level Alarm

A drain-riser water-level instrument should be installed with an automatic alarm for any case where the level in the riser is above a point six inches below the bottom crossheader. The reasons for this drain-riser water-level alarm are based upon difficulties that may and probably will arise if this is not done. For example, as the water level in the drain riser goes above a rear header the back pressure is increased which decreases the tube flow. If a number

of tubes have their rear end caps off or are empty these tubes will receive increased flow at the expense of the rest of the tubes on the header. This will increase the outlet temperatures of the unopened tubes and once boiling starts in a tube it will self pressurize and fuel rupture or melting can result. The initial pressure differential, even if regained, is generally far too low to sweep out the boiling. Thus, it is important to have a functioning drain-riser water-level alarm set to trip at six inches below the bottom crossheader.

Another less desirable solution would be to limit the number of opened rear pigtails and/or end caps to not more than five per cent per header below tube row 23 and not more than ten per cent per header above row 23. Under these conditions the flow by-pass to these opened tubes would not be sufficient to cause tube boiling and burnout in the normal tubes should the crossunder control valve be inadvertently closed.

b. Crossunder Capacity

At the estimated 10,000 to 20,000 gpm capacity of this line there may be up to 24 inches of back pressure in the DR downcomer. This would reduce the flow capacity by about ten per cent. This does not appear to be a serious problem but does indicate the possibility of less than design flow at the DR-Reactor. The actual crossunder line capacity at each reactor should be determined as a part of the A.T.P's. There are two important reasons for having maximum crossunder capacity:

1) To maintain minimum time delay requirements before going to this system after shutdown.

2) To permit a valving condition with minimum flow resistance in the event of a complete power loss at the shutdown area.

Therefore, the crossunder line capacity should be at least 10,000 gpm; and at least 15,000 gpm is required to ensure no increase in the reactor downtime requirements before transferring to this system.

c. Crossunder Line Piping

Basically, this consists of a 16 inch to 18 inch diameter line extending from the base of the near-rear riser to the reactor effluent line and containing a remotely operated shut-off valve. At the DR-Reactor this line extends from the far-rear riser, and at the F-Reactor the line extending from the control valve goes to the 1608 pump house and then to the effluent system.

It is essential that this piping up to and including the control valve be of high integrity. This is true because line failure upstream of the valve or valve failure or inadvertent opening at a time of emergency reactor flow could result in no water flow to the upper rows of reactor tubes. It is true that this implies the occurrence of three separate

simultaneous failures which is very improbable. However, this is partly a matter of semantics, and the word simultaneous can be very misleading. The failure of this crossunder line at any time during a reactor shutdown when for some reason the reactor flow was restricted (by BPA and steam failure, or process line failure, etc.) could lead to no flow to the upper reactor tubes. If this occurred within 20 hours of the reactor shutdown then tube burnout would be probable.

As far as the line material is concerned, a carbon steel line is acceptable provided means for corrosion inspection or monitoring is provided.* The line should be installed in conformance with the appropriate code for earthquake resistance up to an acceleration of 0.20 g.

It should also be installed in a manner that will permit line replacement if necessary.

d. Crossunder Line Valve

The close-off valve on this line must also be of high integrity. It must be operable from the 105 control room under lock and key procedures. There are two basic requirements to prevent the serious but remote possibility of improper valve operation: It must never open when the front crossheaders are unthrottled, it must never close when more than a restricted number of tubes on any crossheader have an end cap and/or pigtail removed.

Because of the considerably greater hazard associated with inadvertent opening of this valve under the conditions of emergency flow and unthrottled crossheaders, this system should have an automatic, rapid (45±15 sec.) valve closing feature that will operate at a TORP $\leq 25 \pm 1$ psig. It is recommended that a standard safety system control device be used with lock-out protection and that this be installed in a similar location in each reactor control room. This will minimize the chance of inadvertent operation and simplify design.

3. Crossunder Operation

a. General

The use of this system involves a basic change in the coolant flow pattern through the reactor. Whereas, the coolant introduced at the front bottom of the reactor and leaving at the rear top established a uniform reactor flow; the use of this crossunder line tends to create a flow imbalance sending most of the flow through the bottom of the reactor and tending to drain the upper tube rows of water. Because of this important change, it is necessary to carefully review the possible effects of the use of this line. This is done in the following sections with certain specific examples chosen to indicate possible problems or desirable operating conditions.

* Personal communication - N. R. Miller

b. Determination of Reactor Flow Distortions Produced by Crossunder Line Operation

1) Vertical Flow Distortions

Before the effects of this crossunder line can be investigated it is necessary to estimate the flow through different sections of the reactor under different conditions of crossheader throttling. The central tube flow for various values of Δp (front to rear header pressure drop) was determined by using Figure A-1 of the Appendix. The total reactor flow, assuming every header throttled in the same manner, was then determined by use of an average EFT value of 1800. Current EFT values for the old reactors are presented as Table A-I in the Appendix.

In this simplified analysis the reactor was divided into two zones:

(a) All headers 23-1/2 and below.

(b) All headers above 23-1/2.

An approximate graphical solution to the problem of determining the flow through these two differently throttled sections of the reactor is presented in Appendix B. In summary, it consists of the following procedure.

(1) Determine the pressure at the intersection of the desired throttled reactor resistance curve with the high-tank supply curve. (i.e., curves presented in Figure A-2)*

(2) Determine the pressure at the intersection of the reactor resistance curve for the other half of the reactor with the high-tank supply curve.

(3) Using the average value of these two pressures determine the flow intersection point of the low-flow reactor resistance curve with this average pressure; and determine the flow point of the intersection of the high-tank supply curve with this average pressure.

(4) Determine the high-flow value according to the equation:

$$\frac{G_2}{2} = G_H - \frac{G_3}{2} \qquad (1)$$

Where: G_2 = The total reactor flow through the unthrottled crossheaders, 1000 gpm.

G_H = Actual high-tank flow, 1000 gpm.

and G_3 = The total reactor flow through the throttled crossheaders, 1000 gpm.

* These resistance curves are plotted for total reactor flow even though only half the reactor is involved.

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The theoretical and graphical methods agree quite closely on the flow through the throttled section of the reactor. Since this is the critical flow this graphical method has been used even though there is about a 15 per cent error in the value of flow through the more open half of the reactor.

The following example typifies the use of this graphical procedure in determining the flow split between the throttled and unthrottled sections of the reactor: Consider the case of the lower half of the reactor throttled to give 300 inches Δp with the uppper half unthrottled. The reactor TORP is 80 psig and the crossunder is closed. Then as shown in Figure A-2 of the Appendix, we have three significant curves:

A. Total reactor resistance in the unthrottled condition.

B. The high-tank supply curve.

C. Total reactor resistance curve for the case of all headers throttled to 300 inches Δp.

The intersection of curves A and B at 19 psig TORP represents the normal high-tank supply flow of 10,000 gpm. This corresponds approximately to the present capacity of the B, D, F and H high tanks. The intersection of curves C and B at 38 psig TORP represents the throttled reactor high-tank flow. The emergency flow through the throttled half of the reactor is that obtained from Figure A-2 for the intersection of the throttled reactor resistance curve, C, with the average pressure = $\left(\frac{38 + 19}{2}\right)$ = 28.5 psig. From the figure this yields a value of 4600 gpm through the throttled half of the reactor.

The high-tank flow, from the same figure, is 8200 gpm. Then the flow through the unthrottled section of the reactor is, according to Equation (1):

$$G_{2/2} = 8200 - 2300 = 5900 \text{ gpm}$$

although the results obtained in this manner are not accurate. There was sufficient difference in the results of the compared cases to justify the use of this approximate method.

2) <u>Horizontal Flow Distortion</u>

In Appendix C to this report the more severe flow distortion effects are described for operation with the crossheaders open to both the rear risers. In addition to this effect which is too severe to

tolerate, it is important to consider two less severe but important variables. These are:

(a) The actual flow path of the coolant through the reactor and accessory piping.

(b) The location of the pressure taps for the front-to-rear header Δp pressure gages that will be used to determine reactor charge-discharge flow.

In general, the flow path should be in one side of the reactor and out the opposite side. For instance, with the front crossheaders throttled on the far side, the rear face flow should be out the near riser which should then be the drain riser. This tends to give a balanced, more uniform flow through the parallel tubes on the header.

In addition to this flow pattern the location of the pressure gages used to determine the front-to-rear header Δp has a significant bearing upon the actual tube flow obtained. In Figure A-1, of the flow versus the header-to-header pressure drop, the header pressure obtained in the laboratory is essentially that pressure adjacent to the entrance of a given channel into or out of the crossheader. On the reactor, however, there may be a considerable difference between the actual header pressure at a given tube and the measured crossheader pressure at the Δp gage.

Typical examples of the effect of the location of the crossheader Δp gages, or taps, are shown in Figure 1. Both curves AA^1 and CC^1 represent a 40 inch Δp between the front and rear headers. There is a significant difference in flow amounting to about 26 per cent, between these two conditions. The location of the tap on the front header is not too sensitive because of the tendency for the velocity head recovery to balance the frictional pressure drop and to yield a constant pressure profile along the header. In the case of the rear headers, however, the velocity head and frictional effects are additive and there is a maximum change in the pressure profile along the header. Conservatively, the pressure taps should be located in the (2,2) position to yield maximum cooling flow. The actual pressure tap locations and the corresponding flow correction factors for the old reactors are presented in Table III.

It has been proposed that this crossunder be operated with the rear riser opposite the drain riser left open to the headers. A theoretical pressure profile along a lower rear header for this type of operation is shown in Figure 1 as curve DB^1. This presents an extreme situation that would be modulated by front-to-rear header interaction. However, inadequate cooling will occur in many of the tubes on this header because the front-to-rear pressure gradient will change severely along the header causing excessive tube flow variation. The details of this pressure calculation are given in Appendix C to this report. We can conclude, therefore, that it will be necessary to valve off the undrained rear riser before using this crossunder system.

FIGURE 1
ESTIMATED CROSS-HEADER PRESSURE PROFILES

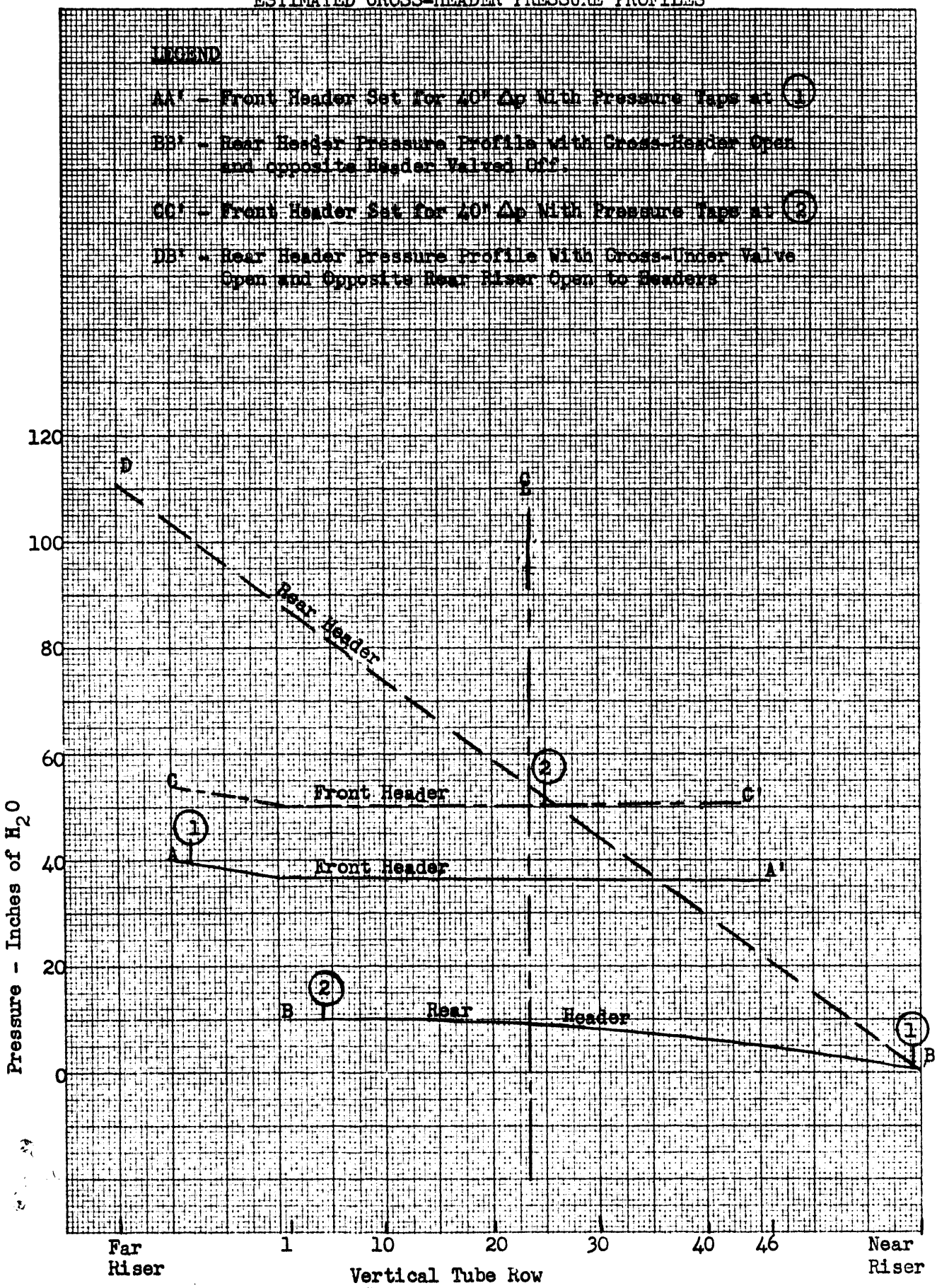

TABLE III

FLOW AND PRESSURE EFFECTS
OF Δp GAGE PRESSURE TAP LOCATIONS

Reactor	Tap Code from Figure 1	Location of Front Tap	Location of Rear Tap	Ratio: Minimum Δp / Measured Δp	Ratio: Minimum Flow / Measured Flow
B,D,F	2,1	Front Header	Near Riser Side of Last Tube	0.85	0.89
DR	2,2	Front Header	Near Riser Side of Last Tube	1.0	1.0
C,H	2,2	Front Header	Far Riser Side of Last Tube	1.0	1.0

c. Determination of Tube Outlet Temperatures

The important aspect of this reactor flow distortion is the resulting high tube outlet temperatures that may occur. The occurrence of tube bulk boiling at these low pressures is very apt to starve the tube of coolant and lead to rupture proneness or fuel failure. Even if boiling is detected special procedures are required to eliminate it; and in the case of emergency (last ditch) water flow, it is very doubtful that there will be sufficient header pressure to sweep out the boiling and prevent fuel burnout. Therefore, it is necessary to avoid tube boiling. The following equation was used in this report to establish the tube outlet temperatures:

$$T_o = T_i + \frac{f_P \, P/E_P}{.264 \, G/E_F} \qquad (2)$$

Where f_P = Heat decay factor: fraction of original equilibrium heat output (see Figure A-6).

P = Total equlibrium power level in MW.

E_P = Number of effective power tubes $\approx$ 1500.

G = Total reactor flow that would exist under conditions of complete crossheader throttling for the chosen Δp: 1000 gpm.

E_G = Number of effective flow tubes $\approx$1800.

T_i = Inlet coolant water temperature: °C.

T_o = Tube outlet temperature assuming no boiling: °C

As presented in the following sections of this report, once the reactor flow distortions were estimated for various reactor conditions, then this equation (2) was used to determine the temperature effects.

d. Going Onto the Crossunder

1) Initial Crossheader Valving

One of the main functions of this new crossunder line is to reduce the amount of crossheader valving required for charge-discharge procedures. A certain minimum amount of valving must be done to maintain adequate reactor cooling or cooling potential and the following conditions must prevail before opening the crossunder valve:

(a) At least 80±5* psig TORP.

(b) All the front crossheaders throttled in succession from the bottom header to the top to give a front-to-rear Δp of:

Not more than 300 inches water.

Not less than 140 inches water.

(c) All the rear header valves closed that lead to the riser opposite the drain riser.

The reasons for the initial valving before opening the crossunder are as follows: The reactor flow must be reduced to a value equal to the capacity of the drain riser which ranges from about 10,000 gpm for F-Reactor to nearly 20,000 for C-Reactor. The reactor flow cannot be reduced to these values by means of the pumps alone without tripping in or valving off the high-tanks and neither action is desirable. Therefore, an initial throttling must be made before opening the crossunder line. Because the opening of this line will cause about a 20 psi drop in the riser pressure it will be necessary to have a high enough TORP to handle this crossunder opening pressure-drop without tripping in the high-tanks.

The reasons for throttling the reactor from the bottom up and within the pressure drop region of 160 to 300 inches of water,

* The basic requirement is sufficient TORP to prevent tripping in the high-tanks when opening the crossunder valve. The A.T.P. tests should establish a more accurate limiting TORP value.

header-to-header, are illustrated by the following examples. In considering these examples it is necessary to recognize two basically different conditions:

(a) Prevention of tube boiling under normal shutdown pumping conditions.

(b) Prevention of tube boiling under emergency conditions during a reactor shutdown.

It is necessary to prevent boiling in the first case because of the high frequency with which boiling could occur if improper procedures or crossunder design were established. In general, the boiling could be swept out by increasing the reactor TORP. However, this would be wasteful of time and manpower. It is necessary to prevent boiling in the second case because little could be done to stop it and severe fuel damage could result. Thus, the various examples presented are considered under there two conditions:

Example A: One-half crossheaders throttled to 300 inches; the other half unthrottled, crossunder line closed (i.e., 5.5 gpm central tube flow through tubes with throttled headers):

The central zone tube flows in the throttled and unthrottled sections of the reactor for 80 psig TORP are shown in Table IV. It is evident that no flow or temperature problems exist under these conditions. Actually, the problems in this case are operational, 300 inches represents the upper limit of the header Δp gages and a rather wide range of flow through this throttled section could result.

Example A^1: Loss of pumping power after valving to condition A:

Table V presents the central tube flows and temperatures in the event of a complete pump loss in the shutdown area. This means a transition from the normal shutdown flow to that available from the high tanks. Export water should also be available after several minutes but the effect of its use has not been added to the emergency flow. Primarily this is because once boiling has started in the hottest central tubes it is improbable that this increased flow will provide sufficient pressure to sweep steam out of these tubes.

The flows and temperatures for this example have been determined according to the procedures described earlier. They indicate no problems under this valving condition, except for the operational problem of the Δp gage inaccuracies in this range and the delay involved in throttling down from 300 inches to the desired 60 to 120 inches Δp for charge-discharge procedures.

Example B: One-half crossheaders throttled to 100 inches, other half unthrottled, crossunder line closed (i.e., 3 gpm central tube flow):

Again an examination of Table IV shows no temperature problems pertaining to this valving procedure. An examination of Table V for emergency flow under these conditions (Case B^1) indicates temperatures of 70°. In view of the approximate methods of this analysis these temperatures are considered excessive. Therefore, the limit of 160 inches has been imposed upon the first flow reduction.

Example C: One-half crossheaders throttled to 40 inches, other half unthrottled, crossunder line closed (i.e., 1.6 gpm central tube flow):

Under these conditions Table IV shows tube outlet temperatures of 60° for normal cooling and 120° for emergency cooling. These values are definitely excessive and this substantiates the recommendation of a higher limiting pressure-drop.

The reason for throttling the headers from the bottom to the top is because of the basic tendency for the coolant flow to by-pass the upper reactor tubes under the conditions of throttled upper headers and opened crossunder line. Actually, whenever the crossunder line opens there are three primary effects.

(1) There is a decrease in back pressure which increases the reactor flow.

(2) There is a diversion of the flow towards the lower tubes of the reactor.

(3) There is a decrease in the tube outlet saturation temperature from about 120°C down to close to 100°C.

A comparison of these effects for the condition of one-half the reactor throttled to 100 inches is shown in cases D,D^1 and E,E^1 in Tables IV and V. These indicate that the opening of the crossunder line does not cause a serious flow distortion. However, for the case of one-fourth of the headers throttled the difference between having the top or the bottom headers throttled should be considerably more pronounced. Therefore, it appears prudent to avoid this flow distortion effect by throttling the headers from the bottom to the top.

This manner of valving tends to maintain the submerged reactor concept that is a basic part of the effluent crossover and downcomer system of each reactor.

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TABLE IV

TUBE OUTLET TEMPERATURES FOR GOING ONTO CROSSUNDER*

(Assume Central Tube = 21 kw, 4 hours After Shutdown)

Case No.	Conditions	Location	Central Tube Flow	Torp	Temperatures Inlet	Outlet	Sat.
A	Bottom 1/2 Reactor Valved to 300" Δp, Crossunder closed	Top 1/2 Reactor	15	80	10	15	115
		Bottom 1/2 "	5.5	80	10	25	120
B	Bottom 1/2 Reactor Valved to 100" Δp, Crossunder closed	Top 1/2 Reactor	15	80	10	15	115
		Bottom 1/2 "	3	80	10	37	120
C	Bottom 1/2 Reactor Valved to 40" Δp, Crossunder closed	Top 1/2 Reactor	15	80	10	15	115
		Bottom 1/2 "	1.6	80	10	60	120
D	Top 1/2 Reactor Valved to 100" Δp, Crossunder Opened	Top 1/2 Reactor	3.3	60	10	34	100
		Bottom 1/2 "	16.9	60	10	15	100
E	Bottom 1/2 Reactor Valved to 100" Δp, Crossunder Opened	Top 1/2 Reactor	16.4	60	10		100
		Bottom 1/2 "	3.4	60	10		100

*Based on 1840 MW initial power and 10°C inlet temperature

[redacted]

TABLE V

TUBE OUTLET TEMPERATURES

FOR EMERGENCY WATER FLOW WHEN GOING ONTO CROSSUNDER

Case No.	Conditions	Time After Reactor Shutdown (hours)	Power Level* Decay Factor	Power Level* Central Tube Power	Location	Central Tube Flow (gpm)	Temperature* Outlet	Temperature* Sat.
A[1]	Power loss after bottom 1/2 reactor throttled to 300", Crossunder closed	0	1	1200	Top 1/2 Reactor	46	117	140
		2	.028	34		6.4	30	112
		4	.0175	21		6.4	22	112
		0	1	1300	Bottom 1/2 Reactor	46	117	140
		2	.028	34		2.6	60	120
		4	.0175	21		2.6	48	120
B[1]	Power loss after bottom 1/2 reactor throttled to 100", Crossunder closed	0	1	1200	Top 1/2 Reactor	46	117	140
		2	.028	34		6.5	29	112
		4	.0175	21		6.5	21	112
		0	1	1200	Bottom 1/2 Reactor	46	117	140
		2	.028	34		1.5	96	120
		4		21		1.5	63	120
C[1]	Power loss after bottom 1/2 reactor throttled to 40", Crossunder closed	0	1	1200	Top 1/2 Reactor	46	117	140
		4	.0175	21		7.1	21	112
		0	1	1200	Bottom 1/2 Reactor	46	117	140
		4	.0175	21		7.2	120	120
D[1]	Power loss after top 1/2 reactor throttled to 100", Crossunder open	0	1	1200	Top 1/2 Reactor	46	117	140
		4	.0175	21		1.56	61	100
		0	1	1200	Bottom 1/2 Reactor	46	117	140
		4	.0175	21		8.6	19	100
E[1]	Power loss after bottom 1/2 reactor throttled to 100", Crossunder open	0	1	1200	Top 1/2 Reactor	46	117	140
		4	.0175	21		8.2	20	100
		0	1	1200	Bottom 1/2 Reactor	46	117	140
		4	.0175	21		1.9	52	100

*Based on 1840 MW initial power and 10°C inlet temperature.

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The reason for item (4) valving off the other rear riser are explained in Appendix C to this report. Basically, it is because leaving this riser open would introduce a severe pressure gradient along the lower rear crossheaders. This would mean that the measured Δp (front-to-rear header) would not truly represent the flow conditions in these header tubes. In fact, as indicated in Figure 1 the excessive rear crossheader pressure drop along the lower rear headers might cause zero flow in some of the tubes on these headers. Severe tube and fuel damage could result and this type of operation is not acceptable.

2) Final Crossheader Valving

After the initial crossheader valving is completed and the crossunder is opened it will be necessary to complete a final crossheader valving to obtain balanced reactor flow. This will impose a vertical throttling gradient to balance the vertical static head gradient that exists when the crossunder is opened. Again, the limitations to be imposed for safe operation under these conditions are best obtained by comparing typical examples.

Example AA[1]: Bottom one-half reactor headers valved to 40 inches Δp, top half valved to 300 inches, and the crossunder open:

As shown in Tables VI and VII, adequate cooling is obtained for this case even after a complete power failure; provided there has been a delay before valving of at least four hours after the shutdown.

Example BB[1]: Bottom one-half reactor headers valved to 40 inches Δp, top half valved to 300 inches and the crossunder closed:

In this case reclosing the crossunder valve results in about a seven per cent flow reduction at the top of the reactor and 15 per cent at the bottom. This decrease in flow tends to be balanced by an increase in the outlet saturation temperature. This increase amounts to 12 per cent at the top of the reactor and 20 per cent at the bottom. Thus, the pressurization effect actually exceeds the flow decrease effect produced by closing the crossunder valve. This indicates that rapid closure of the crossunder valve upon loss of pumping power is not essential once the initial valving step has been completed.

In order to obtain maximum cooling adequacy and flow distortions, upon loss of pumping power, that do not exceed acceptable values the following limitations are imposed:

(1) The second valving process should also be carried out by valving in succession from the bottom header upwards.

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TABLE VI

TUBE OUTLET TEMPERATURES FOR CROSSUNDER VALVE POSITIONS*

(4 hours after shutdown - 21 KW/Central Tube)

Case No.	Conditions	Location	Central Tube Flow (gpm)	TORP	Temperatures Inlet	Outlet	Sat.
A	Bottom 1/2 reactor valved to 40" p, top to 300" p, Crossunder open	Top 1/2 Reactor	5.5	80	10	25	100
		Bottom 1/2 "	1.6	80	10	60	100
B	Bottom 1/2 Reactor valved to 40" p, top to 300" p, Crossunder closed	Top 1/2 Reactor	5.1	85	10	26	112
		Bottom 1/2 "	1.35	85	10	69	120
C	Top 1/2 reactor valved to 40" p, with bottom at 300", Crossunder open	Top 1/2 reactor	1.6	80	10	60	100
		Bottom 1/2 "	5.5	80	10	25	100
D	Top 1/2 reactor valved to 40" with bottom at 300", Crossunder closed	Top 1/2 Reactor	1.35	85	10	69	112
		Bottom 1/2 "	5.0	85	10	26	120

*Based on 1840 MW initial power and 10°C inlet temperature.

TABLE VII

TUBE OUTLET TEMPERATURES
FOR EMERGENCY WATER FLOW WHEN GOING ONTO CROSSUNDER*

Case No.	Conditions	Time After Reactor Shutdown (hours)	Power Level: Decay Factor	Power Level: Central Tube Power	Location	Central Tube Flow (gpm)	Temperature: Outlet	Temperature: Sat.
		0	1	1200				
A[1]	Power loss after bottom 1/2 reactor throttled to 40", top half to 300", Crossunder open	4	.0175	21	Top 1/2 Reactor	4.6	27	100
		6	.0130	15.6		4.6	23	100
		4	.0175	21	Bottom 1/2 "	1.2	76	100
		6	.0130	15.6		1.2	59	100
B[1]	Power loss after bottom 1/2 reactor throttled to 40", top half to 300", Crossunder closed	4	.0175	21	Top 1/2 Reactor	4.1	29	112
		6	.0130	15.6		4.1	25	112
		4	.0175	21	Bottom 1/2 "	1.0	90	120
		6	.0130	15.6		1.0	69	120
C[1]	Power loss after top 1/2 reactor throttled to 40", with bottom half at 300", Crossunder open.	4	.0175	21	Top 1/2 reactor	1.08	84	100
		6	.0130	15.6		1.08	65	100
		4	.0175	21	Bottom 1/2 "	4.8	26	100
		6	.0130	15.6		4.8	22	100
D[1]	Power loss after top 1/2 reactor throttled to 40", bottom 1/2 at 300", Crossunder closed	4	.0175	21	Top 1/2 reactor	.93	96	112
		6	.0130	15.6		.93	74	112
		4	.0175	21	Bottom 1/2 "	4.2	28	120
		6	.0130	15.6		4.2	24	120

*Based on 1840 MW initial power and 10°C inlet temperature.

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(2) To facilitate charge-discharge procedures, certain of the crossheaders, containing no tubes scheduled for discharge, may be left in the first 160 inches to 300 inches Δp throttled condition. The following restrictions apply to this condition:

Crossheader Location	No. of Headers That May Be Left at 160" to 300"
Below 23-1/2 Header	3
Above 23-1/2 Header	6
Maximum No. of Headers in Central Zone	5

The reasons for the first restriction are similar to the reasons for making the initial crossheader throttling from the bottom header upwards. The consequences of making this second throttling from the top instead of the bottom are not as severe, but in view of the negligible time loss imposed by this restriction and the definite increase in cooling adequacy it is recommended that this second throttling procedure should also be made in order from the bottom header upwards.

In the case of crossheaders with no tubes scheduled for discharge it would save some time to leave them at the initial 160 inches to 300 inches p throttling. However, these more-opened headers tend to by-pass reactor flow from the other headers.

A condition probably considerably more severe than normally expected is shown as cases C,C[1] and D,D[1] in Tables VI and VII. These indicate that for as many as 50 percent of the headers unthrottled (i.e., initial throttling only) normal shutdown temperatures could exceed the standards limit of 60°C; and somewhat higher temperatures would be obtained under emergency conditions. These tables do not show the more severe conditions that would exist with the crossunder line open and a number of throttled headers set-up for charge-discharge. Therefore, it is advisable to considerably restrict the number of unthrottled headers. These restrictions will reduce the chance of obtaining tube damage or fuel meltdown upon a pump failure or BPA loss during charge-discharge.

e. Charge-discharge With Crossunder Line Open

There are two types of conditions for which the adequacy of cooling and proper operation of this crossunder system must be considered. These are:

1) The effect of variations in the charge-discharge procedures such as:

   a) Number of tubes on header with rear end caps removed,

   b) Number of tubes on header with front end caps removed,

   c) Number of empty tubes on header,

   upon the adequacy of cooling with normal shutdown pumping capacity.

2) The effect of the loss of normal pumping power and possible closing of the crossunder line upon adequacy of reactor cooling.

The determination of the safe limiting conditions for charge-discharge procedures with respect to nozzle cap removals and number of empty tubes, etc., is a complex problem and will be the subject of another report. The effect of a power failure upon cooling adequacy is illustrated in Table VIII. As noted earlier the closing of the crossunder valve upon loss of pumping power results in a decrease in tube flow and a corresponding increase in tube outlet temperature combined with an increase in the saturation temperature. The net result is no marked advantage for closing the crossunder line once the initial throttling has been completed.

Table VIII shows the flow conditions for normal and emergency flow to the reactor under conditions of partial completion of the second throttling step with the crossunder open and closed. A further important consideration is the effect of a power failure or valve closure during the actual charge-discharge process. Part of the procedure for the use of the crossunder line involves removing all the rear end caps on tubes to be discharged. Thus, on a lower reactor header, the closing of the crossunder line could divert all of the crossheader flow through the opened tubes with no flow through the tubes valved to the crossover. As developed in Appendix D to this report, a point exists for any given flow diversion (i.e., number of rear end caps removed per header) where the pressure drop through the opened tubes just equals the static pressure from the outlet of the closed tubes on this header to the crossover. At this crossheader the flow through the closed tubes is just zero. For all crossheaders below this level the back pressure is even greater and the flow through the closed tubes remains zero. For all crossheaders above this there is a gradual increase in flow through the closed tubes.

The severity of this effect depends upon the number of rear end caps that must be removed before crossunder closure becomes a problem and the number of crossheaders that would be adversely affected by the valve closure. For instance, Table A-V indicates that for the case of 25% of the reactor tubes drained (i.e., 25% of the tubes on each

TABLE VIII

TUBE OUTLET TEMPERATURES FOR POWER LOSS DURING CHARGE-DISCHARGE

Case No.	Conditions	Time After Reactor Shutdown (hours)	Power Level: Decay Factor	Power Level: Central Tube Power	Location	Central Tube Flow (gpm)	Temperature: Outlet	Temperature: Sat.
		0	1	1200				
A[1]	Power loss after all reactor throttled to 40", crossunder open	4	.0175	21	Top 1/2 Reactor	1.3	71	100
		6	.013	15.6		1.3	56	100
		4	.0175	21	Bottom 1/2 "	1.3	71	100
		6	.013	15.6		1.3	56	100
B[1]	Power loss after all reactor throttled to 40", Crossunder closed	4	.0175	21	Top 1/2 Reactor	1.21	76	112
		6	.013	15.6		1.21	59	112
		4	.0175	21	Bottom 1/2 "	1.12	81	120
		6	.013	15.6		1.12	63	120

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header with their rear end caps off) there would be no flow to any closed tubes below the level of the 15-1/2 crossheader. By severely limiting the number of opened tubes on a header it is possible to assure adequate flow to the closed tubes. However, this defeats the purpose of the crossunder line by complicating the charge-discharge procedure.

The two obvious solutions to this problem are to either:

(1) Limit the number of front or rear end caps (or pigtails) removed on a header to:

(a) 5 per cent on any header below 23-1/2,

(b) 10 per cent on any header above 23-1/2, or

(2) Prevent sudden closure of the crossunder valve whenever the percent end caps removed exceeds (1) above.

Another important consideration in the use of this crossunder line for the actual charge-discharge is the monitoring of tube outlet temperatures. It will be important to monitor the outlet temperature of the tubes on each crossheader being throttled and to avoid exceeding the Process Standards limit of 60°C. The reasons for this are both to prevent tube boiling and to avoid the compounding of problems that would be associated with sweeping out boiling if it occurs. For instance, if a crossheader is returned to approximately 75 psi TORP to sweep out boiling the increased flow may increase the water level in the drain riser above that of the lower crossheaders. This, in turn, could cause boiling in the hottest tubes on these headers, etc. Thus, accurate flow control and thorough outlet temperature monitoring are an important part of the charge-discharge procedure.

f. Going Off the Crossunder

To return to the normal effluent flow system the procedure for going onto crossunder line should be reversed. However, the return to the normal flow system will be made 20 to 30 hours later in the shutdown than the going onto this crossunder system. Therefore, the degree of hazard is considerably reduced and certain simplifications in the procedure are permissible. In general, the following procedure should be used:

1) Put on all process tube end caps and pigtails.

2) Close the crossunder line valve and lock in the closed position.

3) Completely open all the throttled front crossheader valves in succession from the bottom header upwards while maintaining a reactor TORP of 70 ± 5 psig.

4) Completely open all the rear crossheader valves to the undrained riser.

This method of return to normal effluent flow will ensure that a power failure does not cause the top third of the reactor to drain dry of water.

4. Program

As previously noted this is a preliminary report based upon incomplete information and approximate analytical procedures. In order to cover the use of this crossunder line adequately, a continuing program of testing and analysis is recommended. Such a program should include the following items:

a) Experimental Tests

As a part of the completion of this project at each reactor a series of A.T.P. tests will be performed to ensure that the crossunder assembly satisfies the design requirements. At the same time it would be advisable for the process engineer to run any additional tests required to determine the adequacy of the system under emergency conditions.

b) Flow Analysis

Following the completion of these experimental tests it may be necessary or desirable to make more complete analytical studies of the flow problems that arise from the use of this system.* Such an analysis would be considerably helped by the use of the McIlroy analyzer available, by contract, at the Hydraulics Laboratory of the Washington State University.

c) Along with the analysis of the over-all reactor flow distortions an analysis and experimental tests are needed to determine the crossheader flow distortions resulting from:

1) Various numbers of tubes with their rear end caps removed.

2) Various numbers of tubes with their rear and/or front end caps removed.

3) Various numbers of empty tubes.

d) The results of this report apply to the B, D, DR, F and H Reactors. It is important that a similar analysis be applied to the C and K Reactors, taking into consideration any differences in the piping or flow conditions that exist at these reactors. The approximate analytical procedures presented as Appendices to this report should indicate where problem areas exist and where operating changes or more accurate information is required to ensure adequate reactor cooling under emergency conditions.

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* It is important to note that this charge-discharge procedure and related flow analysis is a long overdue need and is not required just because of the change-over to the crossunder concept.

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S. S. Jones

S. S. Jones
Reactor Engineering Unit
Research and Engineering Section

RECOMMENDATIONS APPROVED:

R. E. Trumble

R. E. Trumble, Supervisor
Reactor Engineering Unit
Research and Engineering Section

SSJ:vb

DATE
FILMED
6/15/94

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