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PRESSURIZING NEW REACTORS

INTRODUCTION

The Technical Division was asked recently to consider designs for new reactors that would add 8000 capacity to the Savannah River Plant. One modification of the existing SRP design that would enable a higher power rating, and therefore require fewer new reactors, is an increase in the minimum pressure in the D₂O system. The existing reactors at SRP are designed for a maximum pressure in the gas plenum of only 5 psig. Higher pressures enable higher D₂O temperatures and higher sheath temperatures without local boiling or burnout. The requirements in reactor cooling facilities at any given power level would therefore be reduced by pressurizing.

SUMMARY

A power output of 4000 MW might be attained with a single new reactor by making the following major changes in the design: 1) Increase the operating pressure on the reactor tank from atmospheric to 60 psig. 2) Increase the D₂O circulation from the present 90,000 gpm to 150,000 gpm. 3) Increase the cooling H₂O flow to the heat exchangers from 90,000 gpm to 250,000 gpm, and 4) Increase the heat exchanger

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surface from 400,000 sq ft to 900,000 sq ft. A power output of 2800 MW might be attained if only the first two modifications mentioned above are introduced.

Increasing the pressure on the main reactor tank to 60 psig may introduce serious design problems. An alternate method of obtaining the beneficial effects of increased pressure would be to construct a second plenum in the bottom of the reactor so that the cooling water would flow directly from the fuel elements to the suction of the main process pumps. With this arrangement, the minimum pressure on the main circulating stream could be maintained at 70 psig in the bottom plenum and the moderator could be maintained at essentially atmospheric pressure. Primary consideration is given in this memorandum to the use of a bottom plenum.

The 60 psi increase in pressure on the coolant system is a minimum increase to be considered because it corresponds to the onset of fully developed local boiling at a maximum sheath temperature of 200°C. A sheath temperature of 200°C seems to be the upper limit for aluminum cladding from the standpoint of corrosion. It may well be feasible to operate in the regime of incipient local boiling. If it is desired to keep safely away from local boiling, an increase in pressure on the coolant system of 200 psi is required. This is the conservative recommendation if 200 psi can be realized without appreciably more complication than is involved for a 60 psi increase.

Any higher pressures than considered above cannot be exploited unless sheath temperatures in excess of 200°C become feasible with aluminum cladding. Zirconium cladding would solve the problem of corrosion for sheath temperatures considerably in excess of 200°C. A process for separating irradiated fuel from zirconium must be demonstrated, however, and a cost estimate prepared before an economic evaluation can be made of higher pressures with zirconium cladding.

SCOUTING

The effect of higher pressures on cooling requirements was scouted by considering a few cases. These cases are summarized in Table I. The objective was to jack the rating of a C-type reactor to 4000 MW. The basis for these calculations are as follows:

- 1) the maximum sheath temperature is the point of incipient local boiling;

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2) the D_2O effluent from fuel elements generating maximum power is below the saturation temperature corresponding to the pressure in the gas plenum;

3) the fuel element consists of two concentric tubes of natural uranium with the coolant flowing in series through the channels, emerging from the central tube which is 1.437 inch diameter;

4) the D_2O circulation is 150,000 gpm in order to not exceed a maximum velocity of 50 ft/sec., and

5) the flattening and zoning is the same as for C-reactor.

The existing upflow cooling system was employed for this scouting by considering the gas plenum as being pressurized, as a simplification of concept. Other conceptions are discussed below. Basis No. 2 above means merely that a margin of about 10 psig is provided on the vapor pressure of the D_2O in a bottom plenum.

The maximum sheath temperature for a particular gas plenum pressure is estimated first. The temperature of the D_2O emerging from fuel elements generating maximum power and the D_2O plenum temperature were then estimated, according to the power level. Since the D_2O circulation was fixed at 150,000 gpm in order not to exceed a velocity limit of 50 ft/sec., a higher power level requires a lower D_2O temperature (for greater ΔT from fuel sheath to coolant), unless the gas plenum pressure is also increased in order to raise the maximum sheath temperature for incipient local boiling. The cooling H_2O and heat exchange surface required to achieve the estimated temperature in the D_2O plenum at the prescribed power level are then calculated. The details on these estimates are given in the Appendix.

Table I shows that power level of 2400 MW is possible with atmospheric pressure on the gas plenum (Case 1). The temperature of the D_2O effluent from the central fuel approaches closely the saturation temperature at the top of the tank, a tentative limitation. The minimum cooling requirements are 494,000 sq. ft. heat exchange surface with 163,000 gpm cooling H_2O . A power level of 3000 MW is possible with somewhat less in cooling facilities by increasing the pressure in the gas plenum to 30 psig. (Case 2.) The heat exchange surface is cut in half by employing a gas plenum pressure of 60 psig (Case 3). Less H_2O and more area would have been more economical on the basis of Figure 3, but 144,000 gpm H_2O is required in order not to exceed an H_2O temperature of 100°C. The maximum sheath temperature prescribed for incipient local boiling increases from 147°C at 0 psig gas plenum to 199°C at 60 psig. A power

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level of 4000 MW is possible with 60 psig gas plenum pressure and 199°C maximum sheath by providing 770,000 sq. ft. heat exchange surface with 215,000 gpm H₂O (Case 4). The D₂O plenum temperature would be 32°C, the temperature of the D₂O effluent from the central fuel would be 131°C, the saturation temperature corresponding to the pressure in the gas plenum would be 154°C.

Table II shows the power levels attainable with 0 and with 60 psig gas plenum pressure using 400,000 sq. ft. heat exchanger surface, as in the existing C-reactor, and H₂O flows currently available or contemplated for C-reactor. With 90,000 gpm cooling H₂O the power level is limited to 1740 MW at 0 psig gas plenum pressure by the D₂O temperature from the maximum fuel reaching the limit of 102°C. The maximum sheath temperature is below the limit for incipient local boiling. A gas plenum pressure of 60 psig enables a power level of 2830 MW, a 60% increase. With a cooling H₂O flow of 135,000 gpm to the exchangers the power rating is 2260 MW for 0 psig gas plenum pressure and 3400 MW for 60 psig gas plenum pressure, a 50% increase in power.

CORROSION LIMITATIONS

Pressurizing can prevent local boiling during normal operation and can provide protection against burnout. Corrosion of the aluminum sheathing at the higher sheath temperatures which pressurizing would otherwise allow must be carefully investigated, however. There are data that indicate acceptable corrosion rates up to 200°C; somewhere beyond this temperature intergranular corrosion becomes serious. Corrosion is subject to subtle effects, however. The tests must closely simulate SRP conditions. Further research is certainly desirable before a design can be based on a sheath temperature of 200°C with aluminum. However, this work might be completed within a year. Existing data may provide upon analysis an adequate basis for proceeding with design.

The sheath temperature could greatly exceed 200°C if zirconium cladding were used. Tubular fuel elements appear to be more readily fabricated with zirconium cladding than with aluminum cladding. The problem of chemical separation is more serious than the added cost of zirconium itself. Chemical research may provide a solution, though it is expected to be an expensive one. For the near future it is best not to rely on zirconium cladding. A separation process must be first demonstrated and an estimate of plant investment and operating cost prepared.

A 60 psi increase in gas plenum or in bottom plenum pressure is about as much as can be justified with a surface temperature limitation of 200°C at incipient local boiling; or, 200 psig with a surface temperature limitation of 200°C

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equal to the saturation temperature at that point. Higher pressure would still allow higher D_2O temperatures in the reactor. Higher D_2O temperatures without higher sheath temperatures, however, entail more fuel surface area and/or higher coolant velocity. Fuel surface is limited to that provided by two concentric fuel tubes; this is a compromise between surface area and the complications in manufacturing and monitoring. A limit on velocity depends upon the erosion encountered, if economic considerations or the complications from fine channels do not act to limit velocity sooner.

CONCEPTUAL CONSIDERATIONS

Atmospheric Tank with Bottom Plenums

Increasing the pressure on the gas plenum leads to problems that might be avoided by using a bottom plenum for collecting the effluent hot D_2O from the fuel elements, leaving the moderator in the tank at atmospheric pressure. The primary problems that arise from pressure on the gas plenum are the tank design for increased pressure, including the lid, and the cooling of the septifoils. Perforated safety thimbles could not be used, moreover. In the case of the septifoils, increasing the pressure on the gas plenum would raise the D_2O into the forest, or higher, above the S-foils. These problems are far from being unsolvable, but they do not seem necessary.

It is conceivable that the moderator could be entirely divorced from the coolant system for the fuel, as in the Canadian's NRX reactor (40 MW rating). The reactor tank for the NRX is like a tube and shell heat exchanger, hence it is called a calandria. It is built of aluminum. The moderator is in the shell side. The fuel is in process tubes which are charged to the tubes of the calandria and separated from them by an annulus of gas. A large production reactor would probably consist of large semipermanent zirconium tubes extending through the top and bottom shields (or tube sheets), sealed with O-rings backed up with packing. A helium annulus would separate the process tubes containing fuel from the zirconium tubes of the tank. The lattice spacing would undoubtedly have to be increased above the 7-1/2 inch distance between centers of the present SRP design, if the same size fuel elements were to be employed. This concept was put aside in favor of the one discussed below. It should be noted that the Canadians did not choose the NRX scheme for their big NRU reactor.

The scheme selected for this memorandum employs an upflow plenum at the bottom of the tank in addition to a bottom plenum for the hot D_2O . The upflow plenum supplies coolant to control septifoils and to the reactor tank. The upflow plenum

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is located between the bottom of the tank and the hot D_2O plenum. Both these plenums might be considered as formed by baffle plates at the bottom of the tank.

Upflow System

An upflow plenum is created in the bottom of the tank, as shown in Figures 1 and 2. Overflow occurs at the top of the tank. Part of the upflow passes through the septifoils for cooling the control rods and discharges at the top of the tank.

The pressure in the upflow plenum is determined by the flow required for cooling the control rods. A flow of 14,000 gpm cold D_2O to the septifoils is estimated to be adequate for a power level of 4,000 MW. The D_2O temperature rise in the hottest septifoil channel would be $20^\circ C$, based on DPSP-55-383. A pressure of 67 psig in the upflow plenum is required for 14,000 gpm flow through the septifoils. This pressure happens to be essentially that desired in the hot D_2O plenum beneath for a 4000 MW power level with $200^\circ C$ maximum sheath temperature at incipient local boiling. Thus, the pressure in the upflow plenum can be equalized with that in the bottom hot D_2O plenum, as in Figure 1. If the pressure in the upflow plenum must differ from that in the bottom hot D_2O plenum, then the upflow plenum must be isolated, as in Figure 2. This latter scheme is indicated if a higher pressure is desired in the upflow plenum than in the bottom hot D_2O plenum in order to provide more flow to the septifoils than indicated above. This latter scheme is also indicated if the bottom hot D_2O plenum is pressurized to 200 psig in order to maintain a $200^\circ C$ sheath temperature equal to the saturation temperature at that point; the pressure drop across orifices restricting the flow to the septifoils would probably be considered excessive from the standpoint of erosion and economics.

The required upflow through the tank, i.e., the moderator flow, depends upon the heat load and upon the design value for the maximum D_2O temperature in the tank. The heat load in the reactor tank derives from the moderation of neutrons and attenuation of gammas, from the leakage of hot D_2O from the bottom hot D_2O plenum, and from transfer through the outer housing tubes of the fuel. Heat transfer through the housing tube can be neglected since the series-flow design of the fuel element has the coldest D_2O in the outer annulus. The leakage of hot D_2O to the reactor tank depends upon the design, possibilities of which are discussed below; this leakage must be kept within bounds. The heat of moderation and attenuation amounts to about 5% of the reactor power for natural uranium loads or about 9% of the reactor power for enriched alloy loads, the case for natural uranium being considered here.

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Separate pumps and heat exchangers may be provided the upflow system, as in Figure 1, or the overflow from the top of the reactor may be boosted to the suction of the main process pumps, as in Figure 2. In either case the pressurizing is done by the pumps taking the overflow from the top of the reactor tank, i.e., by the upflow or booster pumps.

Leakage

Hot D_2O can leak to the moderator at the pin nose in certain designs. The leakage can be reduced by employing tighter fits or by using piston ring seals. Both these measures have disadvantages.

Leakage at the pin nose can be avoided by extending the housing tube through the upflow plenum to mate with the pin nose in the hot plenum, as shown in the alternate schemes in Figures 1 and 2. This puts stringent requirements on straightness and alignment; perhaps a tapered bottom fitting and a slender pin nose could be developed.

Leakage from the hot plenum to the moderator can also be greatly reduced by equalizing the pressures in the upflow and hot D_2O plenums, as in Figure 1. Local and periodic variations in pressure would give some breathing between the upflow plenum and the hot D_2O plenum, but no net flow. This breathing, of course, would warm up the coolant in the upflow plenum and lower the temperature of the D_2O in the hot plenum. No breathing was considered here. Breathing between the two plenums would be reduced by increasing the resistance to flow between them.

The basis for estimating the leakage rate and hence the heat load on the upflow system is given in Table V.

Pressurizing

The bottom hot D_2O plenum is pressurized by the upflow or booster pumps. The overflow at the top of the reactor exceeds the flow from the upflow plenum by the amount of leakage that occurs from the bottom hot D_2O plenum and from the pin noses. The leakage will vary with each loading because of the necessary tolerances.

The booster pump for the scheme in Figure 2 handles the flow to the upflow plenum and the leakage from the main process system to the upflow system. Both the upflow and leakage increase as the pressure in the bottom hot D_2O plenum increases. The static head in the bottom hot D_2O plenum increases. The static head in the bottom hot D_2O plenum decreases, however, as the flow through the booster pump increases because of the nature

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of the head characteristic of the booster pump. This interaction gives a stable pressure in the bottom hot D₂O plenum.

Pressurizing for the scheme having a separate heat exchanger loop for the upflow system, as shown in Figure 1, is accomplished by returning the leakage from the bottom hot D₂O plenum and from the pin noses to the suction of the main process system. This return flow is regulated by the pressure in the bottom hot D₂O plenum. However, throttling the flow by automatic controllers from a point between the upflow pump and the upflow heat exchangers, as shown by a dashed line in Figure 1, is not necessary when the pressure in the upflow plenum is equalized with that in the bottom hot D₂O plenum, which is the case shown in Figure 1. The leakage can be returned through the clearances in the plate separating these two plenums. The cost for heat exchange surface and cooling H₂O will be slightly higher by this device.

The overflow to the booster or upflow pump takes off the side of the reactor tank at a level below the top shield. The changes in the volume of D₂O in the entire system as a result of temperature changes are accommodated by overflow from the gas plenum as in the existing units. Thus, the suction piping to the booster pump remains full of liquid with thermal expansions and contractions.

Main Process Pumps

The capability of a particular process pump was not a factor for consideration here. Certainly there are pumps to do the job. The net positive suction head (NPSH) available for the process pumps increases directly with any increase in pressure on the tank or in the bottom hot D₂O plenum. In a new reactor the submergence of the pump could be increased if necessary. The Bingham process pumps now being built for C-reactor will certainly be adequate for the case given in Figure 1 with the same submergence of 36 feet as in the existing SRP reactors. It is not wise to extrapolate the NPSH characteristic of the Bingham pump to include the case in Figure 2.

FLOWSHEETS

The heat balance and requirements in cooling facilities are presented for two possibilities in Figures 1 and 2, respectively. There are several points of difference, however, so that the two cannot be compared directly. For both cases the power level is 4000 MW.

Separate heat exchangers for the upflow system are considered in Figure 1. The booster pump is considered in Figure 2. The upflow plenum in Figure 1 is built so that the

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pressure in the upflow plenum is equalized with that in the bottom hot D_2O plenum. The upflow plenum in Figure 2 could operate at a pressure significantly different from that in the bottom hot D_2O plenum; however, as pointed out above, the pressure required for the desired upflow through the control septifoils is about the same as that desired in the bottom hot D_2O plenum for a $200^\circ C$ sheath temperature at incipient local boiling.

The overflow from the reactor tank in the upflow system is $60^\circ C$ for Figure 1 and $50^\circ C$ for Figure 2. The leakage of hot D_2O to the upflow at the bottom of the tank is 1200 gpm for Figure 1 and 5000 gpm for Figure 2. The leakage is lower in Figure 1 for two reasons: the pressure in the upflow plenum is equalized with that in the bottom hot D_2O plenum, and piston ring seals are used where the housing tube mates with the nose of the monitoring pin. The D_2O in the tank is hottest near the top of the tank just before mixing is effected with the relatively cool effluent from the control septifoils. Thus, before the mixed temperature of $60^\circ C$ is effected for the D_2O overflow in Figure 1, the D_2O in the tank attains a temperature of $80^\circ C$. The maximum D_2O temperature in the tank is $54^\circ C$ for the case of Figure 2 where the overflow is at $50^\circ C$. It might be beneficial to direct the septifoil effluent, as it flows from the space between the poison plate and the top shield, into the tank near the axis.

The requirements in cooling H_2O and heat exchange surface given in Figures 1 and 2 are greater than those indicated in Table I. This occurs because of the much larger circulation allocated the upflow system. All cases consider a D_2O flow to the high pressure (cold) plenum of 142,000 gpm. Table I considered a cold upflow of 8000 gpm, giving a total of 150,000 gpm at the process pumps.

J. S. Neill

JSN/s

TABLE I

EFFECT OF PRESSURE ON POWER LEVEL AND REQUIREMENTS
IN COOLING FACILITIES

C - Reactor Lattice

Two concentric tubes of natural uranium
(inner tube i.d. = 1.437 inches, housing tube o.d. = 3.40).

150,000 gpm D₂O circulation (48 ft/sec. max. in above fuel element).

Maximum sheath temperature & incipient local boiling.

Economic combination of H₂O and HX area based on DP-23 costs except
where H₂O leaves hxs at 100°C (marked *).

See Table III for details.

Power Level, MW	2400	3000	3000	4000
psig in Gas Plenum	0	30	60	60
Saturation Temperature of D ₂ O in Gas Plenum, °C	102	136	154	154
D ₂ O Temp. exit max. fuel, °C	99	126	150	131
Plenum Temp. °C	40	52	75	32
Max. Sheath Temp. °C	147	179	199	199
gpm Cooling H ₂ O to hxs	163,000	147,000	144,000*	215,000
Heat Exchanger Area, ft ²	494,000	444,000	237,000*	770,000

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TABLE IIEFFECT OF PRESSURE ON POWER LEVEL
WITH EXISTING SIZE COOLING FACILITIES

C-Reactor Lattice

Two concentric tubes of natural uranium

150,000 gpm D₂O circulation21°C cooling H₂O

Power level limited either by the sheath temperature reaching incipient local boiling or by the D₂O temperature from the maximum fuel reaching the saturation temperature corresponding to the gas plenum pressure.

Calculations as for Tables I and III, but employing DPW-54-342 for plenum temperature estimate.

Gpm Cooling H ₂ O to HXs	90,000		135,000	
	0	60	0	60
Psig in Gas Plenum	0	60	0	60
Saturation Temperature of D ₂ O in Gas Plenum, °C	102	154	102	154
D ₂ O Temp. Exit Max. Fuel, °C	102	153	102	143
Plenum Temperature, °C	59	83	46	59
Max. Sheath Temperature, °C	137	199	147	199
Power Level, MW	1740	2830	2260	3400

Figure 1

DPW-56-125

FLWSHEET FOR PRESSURIZED C-TYPE REACTOR WITH ATMOSPHERIC PRESSURE ON MODERATOR TANK — 4000 MW —

- Features:
- 1) Pressure equalized between bottom hot D_2O plenum and upflow plenum.
 - 2) Separate upflow cooling loop.
 - 3) Piston ring seal at pin nose.
 - 4) D_2O overflow @ $60^\circ C$.

FLWSHEET FOR PRESSURIZED C-TYPE REACTOR WITH ATMOSPHERIC PRESSURE ON MODERATOR TANK — 4000 MW —

- Features:
- 1) Pressure in upflow plenum different from pressure in bottom hot D_2O plenum.
 - 2) Booster pump to transfer tank overflow to the suction of the main process pumps.
 - 3) High leakage rate for hot D_2O to tank.
 - 4) D_2O overflow @ $50^\circ C$

Effect of Pressure on Power Level and Requirements in Cooling Facilities - Details for Table 3

Basis

Total Number Fuel Elements N 500

Flow Distribution

end of average / min ϕ_r 0.985
 actual average / min ϕ_s 0.696

Tentative Fuel Element (average flow channels)

heating tube 3.70 m o.d., 3.60 m i.d.
 cooling tube 3.92 m o.d., 3.95 m i.d.
 cooling tube d_i 1.907 m o.d., 1.937 m i.d.
 maximum length 13.5 ft.
 surface area per fuel element S 20.5 sq ft

Hydraulics

D.C. flow rate in pump 150,000 gpm
 D.C. circulation through heat exchangers 142,100 gpm Flow
 D.C. cold upflow 8,000 gpm
 Hydraulic resistance elements 500 (one flow zone)
 D.C. flow per fuel element 292 gpm
 Max D.C. velocity (in last-pass 1.937" diam tube) $\checkmark$ 48 ft/sec

Heat Transfer*

Max sheath temperature $= T(\text{burnt}) = T(\text{local hot}) = 57 \text{ } ^\circ\text{C} - 54 \left(\frac{1}{\text{Paic}} \right) - \frac{1}{2} = 7.160$

Film heat transfer coefficient $= h = 191.5 (10.1098 \phi_s)^{0.8} = 3920 (10.1098 \phi_s)$

Max heat flux $Q = \left(\frac{1.099 \times 10^6}{1.65} \right) \frac{(100)}{45 \phi_s \phi_s} = h \Delta T = h (T(\text{sheath}) - T(\text{D.C.}))$

* max sheath temperature is considered to occur at end of last pass (1.937" diam tube)

C.C. flow rate

Pump flow rate = 150,000 gpm

Case

pressure in gas plenum p_{gas}
 absolute pressure inside bottom fuel P psia

saturation temperature in gas plenum $^{\circ}\text{C}$ saturation temperature inside bottom fuel $T(\text{sat})$ $^{\circ}\text{C}$ (1) max sheath temperature $T(\text{burnt})$, $T(\text{local hot})$ $^{\circ}\text{C}$

reactor power level MW

max surface heat flux Q Btu./sq.ft. $^{\circ}\text{C}$ ΔT (10.1098 ϕ_s)average film temperature $^{\circ}\text{C}$ film temperature drop ΔT $^{\circ}\text{C}$ bulk D.C. temperature in hot spot (i.e. exit max fuel) $T(\text{D.C.})$ $^{\circ}\text{C}$

(1) check on surface temperature for local boiling:
 from SP-13, Figure 20, pg 41

 ΔT (subcooling) $= T(\text{sat}) - T(\text{D.C.})$ ΔT (superheat) $= T(\text{local hot}) - T(\text{sat.})$ T (local hot)

safety factor on burnout: (see 54.516)

 $h_{00} = 5710 + \frac{1.136}{d_i^{0.75}}$ $Q_{00} = h_{00} [T(\text{burnt}) - T(\text{D.C.})]$ safety factor Q_{00} / Q D.C. temperature rise in central fuel ΔT $^{\circ}\text{C}$ D.C. temperature in plenum $T_p = T(\text{D.C.}) + \Delta T$ $^{\circ}\text{C}$ avg. D.C. temperature rise in fuel $^{\circ}\text{C}$ temperature of D.C. leaving reactor $^{\circ}\text{C}$ D.C. temperature rise from pump heat $^{\circ}\text{C}$ D.C. temperature at cold end of hot $^{\circ}\text{C}$ T_{hot} $^{\circ}\text{C}$ approach to hot temp. per pass - all, $y = \frac{T_{\text{hot}} - T_{\text{cold}}}{\Delta T}$ $^{\circ}\text{C}$ rise per pass for megawatt $D = \frac{1000 - 100 (\text{MW})}{500 \phi_s}$

D/W

maximum ratio gpm-hr/gpm-hr at 0 hrs (Figure A-1)

maximum flow of cooling D.C. gpm

maximum flow of cooling D.C. for 100°C exit hot $^{\circ}\text{C}$ gpmrise shutoff factor Z (SP-55-355)leakage coefficient, UA Btu./hr. $^{\circ}\text{C}$ ft. ()is area $= 0.45 \text{ sq ft}$, A sq ft.

(2) saturation pressure corresponding to max sheath temperature, psia
 pressure in gas plenum for max sheath temp. & saturation temp, psia

#1	#2	#3	#4
C. Avg.	30 Avg.	60 Avg.	60 Avg.
31	61	91	91
162°	136°	154°	154°
124°	146°	161°	161°
147.3°	172°	198.6°	198.6°
2400 MW	3000 MW	3000 MW	4000 MW
417,000	521,000	521,000	695,000
106°	132.3°	132.3°	176.3°
133.3°	151.5°	174.1°	165.3°
45.0°	53.0°	78.9°	67.3°
99.3°	126°	149.7°	131.3°
24.7°	32°	11.3°	24.7°
33°	31.5°	31°	34°
152° in 142°	179° in 179°	192.3° in 192.3°	195° in 195.6°
15,910	15,910	15,910	15,910
668,000	738,000	680,000	937,000
1.6	1.4	1.3	1.35
59.2°	74.0°	74.0°	98.6°
40.1°	52.0°	75.3°	32.7°
55.1°	65.9°	65.9°	91.9°
75.2°	120.9°	144.6°	134.6°
0.3°	0.3°	0.3°	0.3°
39.8°	51.2°	75.9°	32.4°
.00783	.0102	.0102	.00885
.023	.023	.023	.023
2.94	2.25	1.37	8.06
1.09	1.09	0.25	1.43
162,000 gpm	142,000 gpm	144,000 gpm	215,000 gpm
100,000 gpm	100,000 gpm	100,000 gpm	100,000 gpm
.0005	.0005	.0005	.0005
250,000	325,000	170,000	390,000
444,000 gpm	444,000 gpm	277,000 gpm	770,000 gpm
82	140	232	232
51	109	201	201

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COMMENTS ON TABLE IIIMAXIMUM SHEATH TEMPERATURE

The maximum sheath temperature was estimated for this study by a simplified method: The maximum heat flux was considered to exist at the end of the last pass. This is a reasonable basis for the series-flow fuel element; it is the limit as the number of flow channels in series increases except for the effect of the neutron flux dip in the bundle. The maximum heat flux was estimated without considering the radial flux dip in the concentric tubes. No hot spot factors were employed. Thus, some assumptions are conservative and some are optimistic.

LOCAL BOILING AND BURNOUT

The surface temperature increases linearly with increasing heat flux when the heat transfer mechanism is forced convection. The surface temperature is practically constant with increasing heat flux when the heat transfer is by local boiling--until the heat flux reaches the burnout value where the mechanism for heat transfer changes. Incipient local boiling is considered to be the point at which the surface temperature that can be maintained by forced convection attains the surface temperature for local boiling as the heat flux is increased with a given bulk coolant temperature, coolant flow, static pressure, and geometry.

The sheath temperature for incipient local boiling, as defined, is higher than the saturation temperature of the coolant at the local static pressure. The temperature of the D_2O in the viscous film adjacent to this sheath therefore reaches the saturation point and some boiling occurs in the film before the point of incipient local boiling, as defined, is reached. The extent of such local boiling is insignificant, at least as a heat transfer mechanism. Local boiling certainly is not fully developed. However, the corrosion rate may be affected measurably once the sheath temperature exceeds the saturation temperature even though local boiling is not fully developed.

A complication arises in estimating the point of incipient local boiling because the mechanism has not been as thoroughly studied as forced convection. It is much easier to estimate, and quite conservative to consider, the limiting sheath temperature as the point when the sheath temperature reaches the saturation temperature. The requirements in cooling facilities or in pressure will be greater on this basis than are indicated in this document. The table above shows that, for a maximum sheath temperature of $200^{\circ}C$, the pressure in the gas plenum must be 200 psig rather than 30 psig if the sheath cannot exceed the saturation temperature.

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COMMENTS ON TABLE III (cont'd)

The two methods of estimating the temperature for incipient local boiling were in good agreement for the conditions of this memorandum, as shown in Table III. The first method is that given in DP-23 and used in DP-89. This method is based on McAdam's paper. The second method employs the correlation of L. Bernath (DPW-54-526) for the burnout surface temperature, which is also the surface temperature for local boiling (on the experimental evidence that the surface temperature remains constant with increasing heat flux in the regime of local boiling).

ECONOMIC RATIO OF H₂O FLOW TO D₂O CIRCULATION

Reference DP-23, DP-1
H₂O, hx, and pumping costs as given in DP-23*

$$\frac{T_2 - T_1}{T_1 - t_1} = D/Y$$

TABLE IV

ESTIMATE OF COOLING REQUIREMENTS FOR FLOWSHEET CASES

Reference	Figure 1	Figure 2
<u>Main Process System</u>		
Power = MW/6	3785	4000
D ₂ O flow through hxs, gpm	142,000	204,000
Temperature of D ₂ O exit hxs, °C	32	32
Y = °C approach to H ₂ O temp. in hxs/MW	.0029	.00275
D = °C rise in pile per MW	.02425	.0169
D/Y	8.36	6.03
Cooling H ₂ O to hxs, gpm	206,000	275,000
Z	+.0062	+.0031
UA	360 x 10 ⁶	470 x 10 ⁶
A, sq. ft. hx area	711,000	930,000
Friction loss for bottom fitting, ft.	16	16
" " " fuel, ft.	130	130
" " " top shield, ft.	16	16
" " " plenum, ft.	11	11
" " " piping, ft.	21	43
" " " hxs, ft.	204	268
Pump head	378	468
BHP per pump (6 total)	3050	5150
<u>Upflow System</u>		
Power = MW (1 - $\frac{1}{2}$ - β)	215
D ₂ O flow through hxs, gpm	30,200	
Temperature of D ₂ O exit hxs, °C	32	
Y	.051	
D	.1104	
D/Y	2.16	
Cooling H ₂ O to hxs, gpm	29,000	
Z	-.01585	
UA	44.4 x 10 ⁶	
A, sq. ft. hx area	88,000	
Static head in bottom plenum, ft.	146	146
Submergence of bottom plenum, ft.	-20	-20
Friction loss for piping, ft.	40	45
" " " hx, ft.	25	-
Pump head	191	171
BHP @ 85% eff (one pump)	1930	3700
<u>Total Requirements</u>		
Cooling H ₂ O, gpm	235,000	275,000
HX area, sq. ft.	799,000	930,000
Theoretical HP for H ₂ O pumping	3300	3820
Theoretical HP for D ₂ O pumping	17,200	29,400

TABLE IV. (contd)

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Investment for Cooling Facilities

(including distributives and allocated power facilities)

Cooling H ₂ O	\$24.70 x 10 ⁶	\$27.98 x 10 ⁶
Heat Exchangers	8.95 x 10 ⁶	10.41 x 10 ⁶
H ₂ O Pumping	1.05 x 10 ⁶	1.22 x 10 ⁶
D ₂ O Pumping	7.74 x 10 ⁶	13.23 x 10 ⁶
Total Investment	<u>\$42.44 x 10⁶</u>	<u>\$52.84 x 10⁶</u>

Total Annual Cost for Cooling

Investment @ 16%/yr.	\$6.79 x 10 ⁶ /yr	\$8.45 x 10 ⁶ /yr
Operating Cost for Cooling H ₂ O	0.91 x 10 ⁶	1.07 x 10 ⁶
" " " Heat Exchangers	0.20 x 10 ⁶	0.23 x 10 ⁶
" " " H ₂ O Pumping	0.19 x 10 ⁶	0.22 x 10 ⁶
" " " D ₂ O Pumping	1.02 x 10 ⁶	1.74 x 10 ⁶
Total Annual Cost	<u>\$9.11 x 10⁶</u>	<u>\$11.71 x 10⁶</u>

Basis:

1. D₂O flow to fuel is 142,000 gpm at a plenum temperature (T₁) of 320°C in a C-reactor loading and zoning, corresponding to Case 4 in Table I and Table III.
2. Leakage of hot D₂O to the reactor tank (F_L gpm) is estimated from Table III-A.
3. Upflow through the septifoils (F_s gpm) is estimated from DPST-55-383: 14,000 gpm @ 4000 MW for 15 MW of control rod heat generation (ρ = .00375) with a 20°C rise in the hottest channel; 67 psig is required in the upflow plenum.
4. Metered upflow through the moderator (F_T gpm) is estimated for a moderator heat load of 200 MW (α = 1.057) at a power level of 4000 MW according to specified maximum moderator temperatures (T_m) and overflow temperatures (T_σ) with consideration given to the leakage of hot D₂O from the bottom hot D₂O plenum at temperature T_{bp}:

$$F_T = \frac{F_L (T_{bp} - T_m) + \left(\frac{1.896 \times 10^6}{550} \right) \left(1 - \frac{1}{\alpha} - \rho \right) (MW)}{T_m - T_1}$$

or

$$F_T = \frac{F_L (T_{bp} - T_{\sigma}) - F_s (T_{\sigma} - T_1) + \left(\frac{1.896 \times 10^6}{550} \right) \left(1 - \frac{1}{\alpha} \right) (MW)}{T_{\sigma} - T_1}$$

5. Requirements in cooling H₂O and heat exchangers are estimated as in DPW-55-354 using Figure 3 in this memo to estimate the economic combination of H₂O and heat exchangers.
6. The brake horsepower (BHP) requirement is estimated for a C-type hydraulic system with larger process piping and plenum, as in DPW-55-445; with the new Bingham process pumps, as in DPW-55-353; and with Foster-Wheeler cored heat exchangers. The head loss across these heat exchangers varies with the surface area requirement, A sq. ft., as follows:

$$\Delta H (hx) = 115 \left(\frac{A}{400,000} \right)$$

The head loss across the fuel element having series flow through the channels is 130 ft. at 242 gpm per element. The head loss for the upflow piping system is selected arbitrarily. The pump efficiency is 85%.

7. Investment and operating costs for cooling facilities are from DPW-6149, which are preferred to the costs in DP-23.

TABLE V

LEAKAGE

1. Leakage through the annular passages around 667 tubes, each 4 inches diameter, considered as sharp-edged orifices:

$$F = 186,000 \times \sqrt{\Delta p} \quad , \text{ gpm}$$

$$\Delta p = \text{psi differential}$$

$$w = \text{annulus width, inches}$$

2. Leakage through annulus sleeves:

$$\Delta H = \frac{\rho \times 144}{f} = \left(1.5 + \frac{4f}{D_e} \right) \frac{V^2}{2g} \quad , \text{ ft. head loss}$$

$$f = \text{Fanning friction factor} = \text{function of ReNo.}$$

$$\text{ReNo.} = 300,000 D_e V = 25,000 (d_e) V$$

$$\text{based on } \mu @ 100^\circ\text{C} = \frac{1488 \times 66.4}{.33} = 300,000$$

$$V = \frac{.321 F}{a} \quad , \text{ ft/sec.}$$

$$a = \text{total cross sectional area of annular passages, sq. in.}$$

$$D_e = \text{hydraulic diameter, ft} = \frac{d_e}{12}$$

$$L = \text{length of annular passage, ft.}$$

$$\rho = \text{liquid density, lbs/ft}^3$$

$$\mu = \text{liquid viscosity, lb/ft-sec.}$$

3. Leakage through piston ring seals:

$$\text{gpm per seal} = 0.25 \sqrt{\Delta p}$$

based on SRP design at the high pressure plenum (i.e., 1.5 gpm @ 170 psi differential) with a factor of safety of about 2.

4. Leakage at Pin Nose, present design:

$$\text{gpm per nose} = 0.7 \sqrt{\Delta p}$$

based on an estimated 2 gpm leakage with the normal 8 psi Δp .

COOLING OF EXPOSED FUEL

(A) APPLICABILITY

This standard applies to the cooling of natural uranium fuel after its removal from the reactor. This standard does not apply to fuel tubes suspected to contain ruptured elements.

(B) BASIS

This standard is designed to prevent damage to the aluminum slug cans and quatrefoil wall when the fuel tubes are lowered into the discharge canal or supplied with emergency cooling water in the C&D machines.

(C) STANDARD

Cooling water is to be supplied to the fuel annuli before the can surface temperature reaches 350°C.

(D) REFERENCES

DPSP-55-25-36, "Quatrefoil Quenching Tests," R. H. Layse and E. C. Nelson, 12/22/55.

DPSP-56-320, "Cooling of Fuel During Discharge," L. J. Abate to A. A. Johnson, 1/9/56.

DPST-55-519, "Pyrophoric Materials in Slug Failures," J. W. Croach, 12/27/55.

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