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SUBJECT: Shutdown & Startup Procedure for HRR

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FROM: C. Michelson

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Summary

This report presents a preliminary proposal for startup and shutdown of the HRR. The principal objective has been to develop a procedure for quick startup which represents a definite improvement over pure D_2O startup. Elimination of a full thermal cycle on the system during each shutdown has also been considered important. The procedure suggested stays within the limitations of available pulsafeeder type pumps.

As a quick startup procedure for the HRR, it is proposed that during each routine shutdown sufficient fuel solution be retained in the high pressure system to keep the system above a minimum specified temperature during the shutdown period. Radiolytic gases generated can be removed by a continuous steam vent. Decay heat in excess of requirements for heat losses and venting can be removed by generating steam in one of the main heat exchangers at a low controlled pressure. At time of reactor startup the high pressure system is filled with heavy water that has been preheated to the system equilibrium temperature. The reactor is made critical at this temperature by pumping in concentrated fuel solution. An equilibrium temperature of 374°F is selected. About 70 minutes is required to make the reactor critical. An additional 47 minutes is required to reach an average operating temperature of 482°F.

Criticality Procedure

Three possible methods have been studied for bringing the HRR to critical. Nuclear calculations[1] indicate that it is safe to make the reactor critical at room temperature, and bring it to operating temperature under its own power. This is not an acceptable procedure, however, because of a gas evolution problem. The HRR design is based on the premise of 100% internal recombination. Sufficient copper is included in the fuel solution to assure total internal recombination at operating temperature and pressure. At lower temperatures and pressures, however, the copper is not 100% effective. Gas bubbles tend to appear at relatively low reactor powers. Figure 1[2] indicates the reactor power at which gas bubbles start to appear for a given average reactor temperature and overpressure. Also shown is the power required to make up natural heat losses from the system. The reactor power at which bubbles start to appear for other overpressures is proportional to the overpressure. It is apparent from the graph that high critical temperatures are required if the reactor is to operate at powers in excess of the natural heat losses. The amount of excess power available determines the instantaneous rate at which the reactor can be brought from critical to operating temperature without gas evolution. It may be possible to use gas separators in the outlet lines to allow startup at lower temperatures. Time was not available to investigate this idea in detail.

A second method of startup is to fill the high pressure system with heavy water, and preheat to the desired critical temperature by injecting steam into the main heat exchangers. The reactor is then brought to critical by pumping in concentrated fuel solution. The final operating temperature is reached under reactor power. Gas evolution is not a problem if a sufficiently high critical temperature is selected. This startup method is very safe nuclear-wise, but time consuming because of limitations on the maximum rate of temperature rise due to thermal stress, and the availability of a large capacity boiler for preheating the large fluid inventory.

The startup method tentatively selected for the HRR is a modification of the procedure just outlined. Instead of using steam to preheat the high pressure system, most of this energy requirement is supplied by fission product decay heat. It is proposed that during each routine shutdown sufficient fuel solution be retained in the high pressure system to keep the system above a minimum specified temperature during the shutdown period. Radiolytic gases generated can be removed by a continuous steam vent. Decay heat in excess of requirements for heat losses and venting can be removed by generating steam in one or more main heat exchangers at a low controlled pressure. At time of reactor startup the high pressure system is filled with heavy water that has been preheated to the system equilibrium temperature. The reactor is made critical at this temperature by pumping in concentrated fuel solution.

This method of operation eliminates part of the thermal cycle on the high pressure system. This may be significant leakagewise in a system subjected to frequent thermal cycling. Another advantage is reduction in time required to go critical since the high pressure system already contains part of the critical mass required. This method can be made sufficiently safe nuclearwise by restriction of the fuel and heavy water holdup in the high pressure system.

Critical Temperature

The selection of a critical temperature for the HRR was based on a study of heat losses and venting requirements for the high pressure system during shutdown. The holdup of fissionable material in the high pressure system is in the return piping to the reactor; none is in the reactor proper. Time did not permit a detailed nuclear safety study of this situation. For the purpose of this initial feasibility study it was assumed that if the holdup of fissionable material in the return piping is less than the critical mass of the reactor itself at the holdup temperature, the system can be considered adequately safe. It is recognized, of course, that the possibility of an incident occurring during shutdown which could transfer all fissionable material to the reactor and establish a new critical geometry with a smaller fluid and fissionable material inventory is extremely remote. Detailed nuclear calculations may later show that larger holdup inventories are permissible. In this event the idea of partial holdup of the fuel solution during periodic shutdown will appear even more attractive.

The critical temperature selection for the HRR is based on an operating cycle of two weeks and a shutdown period of two days. The results apply directly to longer operating cycles. Figure 2 [3] shows the amount of heat loss from the high pressure system and the amount of fissionable material which must be held up in the system after shutdown in order to maintain a given equilibrium temperature over a two day period. Also shown is the amount of fissionable material required to make the reactor itself go critical at a given equilibrium temperature. An equilibrium temperature of 374°F was selected for the HRR. At this temperature the instantaneous power addition required to increase the reactor temperature is about 1 MW. This is well below the power level at which gas bubbles start to appear. At lower critical temperatures gas evolution becomes a problem. At higher critical temperatures the large holdup of fissionable material during shutdown becomes a nuclear safety problem.

Thimble Rupture Hazard

In order to maintain an equilibrium temperature of 374°F during shutdown it is necessary to keep the high pressure system at the saturation pressure, 182 psia. The existence of a net positive pressure on the inside of the thimbles during shutdown may constitute a hazard. The thimbles are adequately strong for this condition without external pressurization, but perhaps some unusual circumstance might cause a rupture. In the event a rupture should occur it can be confined to the thimble if some type of closure is provided on the inlet port. If no closure is provided the vapor expansion must be contained by the hot cell.

This would require exclusion of personnel from this area if any thimble inlet ports are open.

Process Design

Most of the process design is similar to that required for other one-region homogeneous reactors. However, no gas separator is needed. A continuous fluid letdown of about 4-10 gpm is required to maintain constant liquid level in the high pressure system. This is due to the pressurizer and circulating pump purges and the fuel feed stream. The dump tank design is slightly different also, in that one of the dump tanks is isolated from the remainder by a valve. This allows the fluid volume displaced by the high pressure system during startup to be isolated from the concentrated fuel feed solution in the dump tanks. Preventing dilution of the fuel feed solution greatly reduces the startup time required.

Process Operation

A simplified schematic of the HRR flowsheet is shown in Figure 3. During normal operation of the HRR the letdown tank remains empty. Fluid letdown from the high pressure system, blowdown from the high pressure steam generator, and a vent stream from the pressurizer are transfereed to the dump tanks. Fission product and radiolytic gases in the letdown pass upward through the entrainment separator and recombiner system. Fuel feed for the high pressure system is taken from the dump tanks. Condensate feed is taken from the condensate tanks.

Prior to shutdown of the HRR to change experiments the reactor load is removed and the fuel solution circulated for several minutes to insure complete recombination of the radiolytic gases. The main circulating pumps are then stopped, the steam overpressure of 1400 psia released, and the dump valve opened. At this instant the high pressure system is at 577 psia.

During periodic shutdown about 35,000 liters of fuel solution is dumped from the high pressure system. Fission product decay heat from the remaining

11,000 liters keeps the high pressure system at about 374°F. An average continuous evaporation rate of approximately 250 lbs/hr is required in the high pressure system to dilute and remove the radiolytic gases being generated. Additional evaporation is required to make up natural heat losses from the system. Decay heat in excess of the requirements for heat losses and venting is removed by generating steam in one or more of the main heat exchangers at a low controlled pressure.

The fuel solution transferred to the dump tanks is slowly cooled to 212°F. The vapor phase is condensed in the recombiner condenser and transferred to the condensate storage tanks. The noncondensables are vented to the cold traps and fission product beds.

As the evaporation process continues the fuel solution concentration in the dump tanks increases. When the concentration reaches 100 g/l, as determined by the fuel sampling system, a flow of condensate from the recombiner condenser is started to maintain approximately constant fluid inventory in the dump tanks. This may be accomplished by a liquid level controller coupled to a valve in the condensate return line. A preliminary study of the chemistry and corrosion problems associated with concentrations of 100 g/l at 100°C and fission product densities of about 200 watts/liter has been made [4]. There appears to be no serious chemistry problem such as solution stability, but a corrosion problem may exist. However, the concentrated fuel solutions are retained in the dump tanks for relatively short periods of time, so the integrated corrosion may still be small. Titanium may be required for the process lines and equipment transferring the concentrated fuel solution to the high pressure system.

During the concentration process in the dump tanks vapor is let down from the high pressure system to carry off radiolytic gases. This loss of fluid from the high pressure system is made up by occasional transfer of fluid from the condensate storage tanks by pressurization. The condensate tanks are equipped with evaporators for this purpose. The exact amount of fluid in the high pressure system is not critical.

At the time of reactor startup the high pressure system contains the hold-up inventory of fissionable material and heavy water. The dump tank contains the concentrated fuel solution and the condensate tanks contain the heavy water inventory for filling the high pressure system. The letdown tank is empty.

Prior to startup of the HRR the condensate tanks are valved off and heated by the evaporators to sufficient steam overpressure to force the condensate into the high pressure system. Before the main circulating pumps are started, 200 psi steam overpressure is applied to the system. This is to prevent boiling due to nuclear surges and to prevent radiolytic gas evolution. After circulation begins the fuel feed pumps are started. As the reactor is brought to critical the letdown stream from the high pressure system is held up in the letdown tanks. This prevents dilution of the concentrated fuel feed solution in the dump tanks. About 70 minutes is required to make the reactor critical at 374°F.

After the reactor goes critical it is brought to operating temperature under its own power. The steam overpressure is slowly increased to 1400 psia. As the fuel solution is heated a volume expansion occurs which is relieved to the let-down tanks. About 47 minutes is required to bring the reactor from critical to full power operation.

Table 1 shows the assumed condition of the reactor system at the time of reactor startup, at the time the reactor reaches critical, and at full power operation. Table 2 shows the important HRR startup parameters.

When the normal operating condition is reached the letdown tank is emptied and the condensate tanks filled with the excess condensate. The dump tank concentration is reduced since only a small continuous fuel feed is required to make up for fuel burnup and letdown.

No xenon override problem exists with this operating procedure since most of this gaseous poison is removed in the off-gas system whenever the steam overpressure is released.

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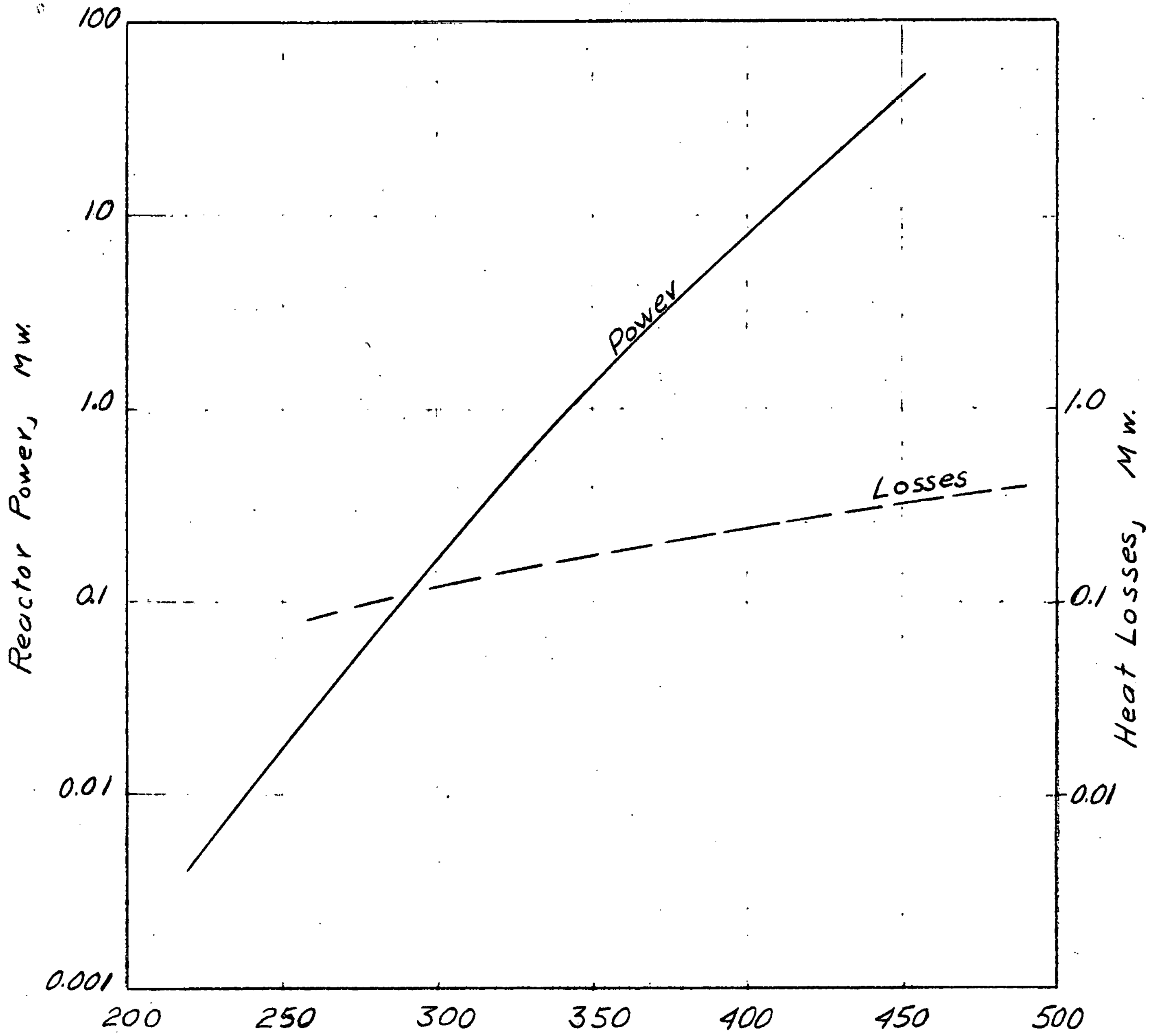

Figure 1

HRR Power Required
to Form Gas Bubbles

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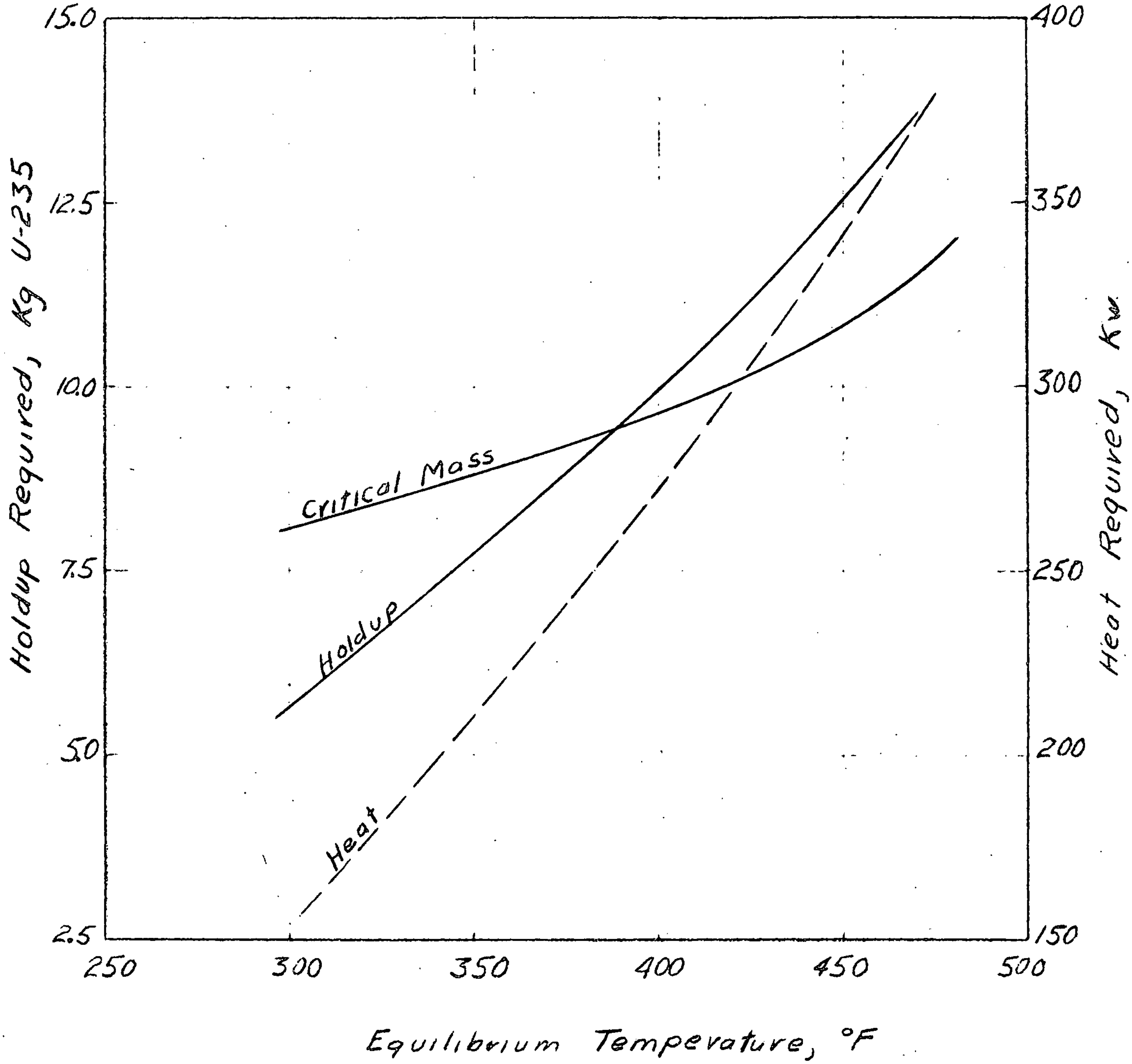

Figure 2

Fuel Holdup in High Pressure System of HRR

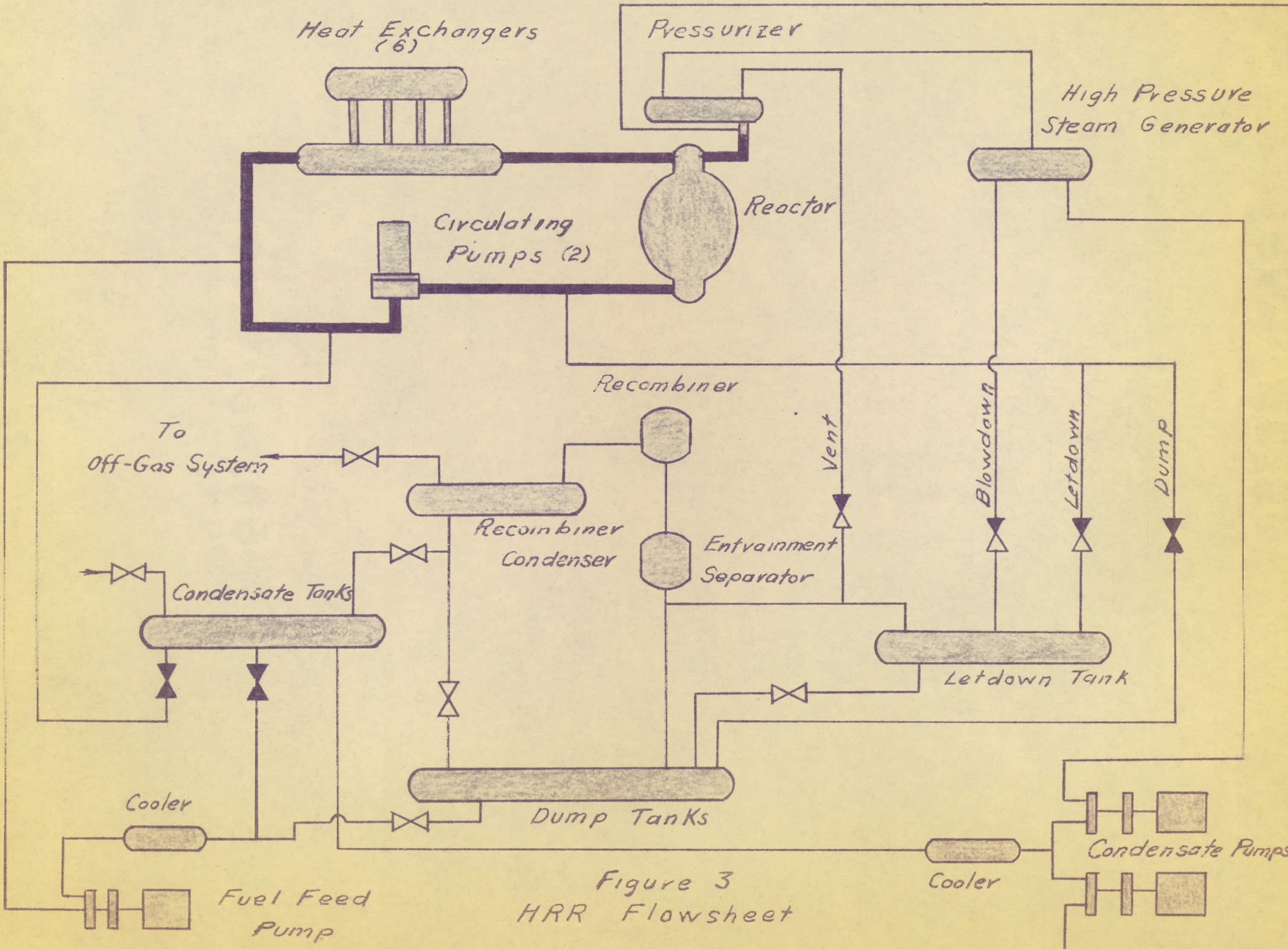

Figure 3
HRR Flowsheet

Table 1

HRR Inventories During Startup

		Startup Kg	Critical Kg	Full Power Kg
High Pressure System	D_2O	9800	44800	40700
	U-235	8.8	28.0	36.8
Let-Down Tank	D_2O	0	3970	10900
	U-235	0	1.8	7.4
Dump Tanks	D_2O	4900	2120	210
	U-235	37	16	1.6
Condensate Tanks	D_2O	38300	2110	1190

Table 2

HRR Startup Parameters

	Startup	Critical	Full Power
Average Temperature, ^{o}F	374	374	482
Pressure, Saturation psia	182	182	577
Total psia	182	390	1400
Time from startup, min.	0	70	110
Rate of Temp. Rise, $^{o}F/min.$	0	0	2.3

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(1) Kasten, P. R., "Control and Start-up of HRR", CF 56-5-124.

(2) Aven, R. E., Personal Communication.

(3) Michelson, C., "Maintaining High Pressure System of the HRR at Temperature After Dump", CF 56-7-38.

(4) McNees, R. A., Personal Communication.