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DISTRIBUTION USE AN ASTERISK (*) TO INDICATE THOSE WHO ARE TO RECEIVE COMPLETE COPIES Complete copies to each person on attached list.	STATEMENT OF PROBLEM Calculate the startup transients associated with starting and restarting an advanced 20 KWe mercury Rankine system in less than one hour without the benefit of neutron flux control.		
M. J. Teresa HQ2 G. E. Dufoe HQ5 J. D. Gordon HQ5 P. M. McGee HQ5 M. P. Berhold HQ2 J. E. Bickel HQ2 J. Goodblatt HQ2 V. Heiskala HQ2	ABSTRACT: A study was made, using a modified version of the primary loop code, to determine the feasibility of starting and restarting the advanced 20 KWe mercury Rankine system in much less time than had previously been done with the SNAP 2 system. The study includes a brief description of a 20 KWe system and discusses the transients obtained for initial preheat, mercury injection, reactor shutdown, and system restart. The analysis demonstrates that a safe startup or restart may be completed in approximately 30 minutes. A discussion is made of a possible problem in the injection phase of startup, if simultaneous injection of all mercury systems is attempted, and a delayed mercury injection method is recommended as a possible alternate. The analysis also concludes that flux control of the reactor is not required, and that the reactor startup procedures and control developed for the SNAP 2 system may be utilized for the 20 KWe system without any major modifications.		
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Brief Description of the Advanced Mercury Rankine System

For the purpose of this study, the advanced 20 KW mercury Rankine power system is considered to be that shown in Figure 1. It may be seen from this schematic that there are five mercury loops in the power conversion system. Only four of these loops will be activated under normal steady state operating conditions with the fifth loop being held in reserve. The steady state mercury flow rate in each power conversion loop is considered to be 21.4 lbs/min total with 5.35 lbs/min of mercury flow through each T/E pump and 4.28 lb/min through each boiler. Steady state NaK flow is 300 lbs/min through the reactor with each T/E pump contributing 75 lbs/min.

Each power conversion loop is assumed to have a separate injection tank with all mercury loops evacuated prior to both the initial startup and subsequent restarts. In the event mercury is dispersed through the power conversion system prior to restart, only slight changes in the injection transients are anticipated.

Due to the fact that the design of the 20 KWe system is not firm, the transients represented are subject to minor change. However, barring major system changes, the transients presented in this report may be regarded as both realistic and conservative. Small changes in mercury or NaK flow rates, NaK piping dimensions, and the presently conceived boiler design, changes will not greatly affect the over-all system dynamics.

Since the initiation of this study, a new modular concept, in which each power conversion system contains mercury loops which pass through only one T/E pump and one boiler, has been advanced and has become the reference design. Although the present analysis is based on each mercury loop splitting and passing through each T/E pump and each boiler, no great difference is expected in the injection transients due to the mercury piping simplification in the newer system. However, the new system will have T/E pumps with external radiators which will produce larger NaK flow rates during the preheat and injection phases of startup. This larger NaK flow rate will tend to damp out reactor power transients. The schematic diagram at the end of this report shows this latest system concept. Future startup and restart simulations are being planned for this system.

Ground Rules

The following ground rules and criteria were used in evaluating the results of this study.

1. Start or restart time is defined as the time elapsed from the startup signal until such time that 20 KW of electrical power may be supplied to the payload.
2. Initial startup time shall be less than one hour.

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3. Startup for the advanced system should be directed toward minimizing the degree and number of modifications to the existing hardware and procedures developed for the SNAP 2 system.
4. Unsafe start conditions shall be avoided. An unsafe start condition is present when the reactor power is increasing on a period of 5 seconds or less.
5. The reactor can withstand coolant outlet temperature transients of 8°F/sec for an indefinite period of time and up to 30°F/sec for 20 seconds.
6. Reactor power transients of not more than 275 KW (uncertain) can be tolerated for short periods of time.
7. The reactor source level shall be an artificial source which will generate 0.1 watt. This will be the source level for the first startup only.
8. The drums are considered to be initially 115 degrees from there full in position.
9. The reactor source level prior to restart is 1 watt which is due to photo neutrons.
10. The system must be capable of safely restarting within one hour after shutdown.
11. No xenon poisoning need be considered at restart because it is negligible for the SNAP 2 reactor.

The minimum start or restart time for the system could be achieved by flux control of the reactor up to sensible heat generation. Flux control of the reactor is accomplished by providing accurate neutron monitoring instrumentation coupled with a sensitive period controller. The startup scheme would then allow the reactor to be brought up to sensible heat generation (approximately 100 watts) on a 5-second period. This method of control would allow an extremely rapid reactivity insertion up to sensible heat. Reactivity insertion after sensible heat generation would be affected by the reactor temperature transients and would require a temperature rate control system similar to that developed for the SNAP 2 system.

Flux control of the reactor is not desirable in that it would complicate the reactor control during startup and would require an additional development effort. Neutron monitoring instrumentation would have to be developed which could operate accurately over a large neutron level (10^{-1} to 10^7) and be capable of withstanding the stringent conditions imposed upon it by the reactor and space environment. It has hence been the objective of this study to attempt to safely start and restart the system without the benefit of flux control while at the same time holding start time down to less than one hour.

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Method of Analysis

The analysis was conducted by utilizing a modified version of the SNAP 2 primary loop code. This code includes mathematical models of the reactor, T/E pump, controller, boilers, and related piping in the primary loop. The reactor model utilizes a five node heat transfer model coupled with reactor kinetics equations containing 6 delayed groups of neutrons and reactivity feedback from the reactor grids and fuel elements. The reactor controller model consists of a simple digital logic circuit which activates the control drums during preheat and startup. The controller is coupled to a temperature sensor located on the boiler inlet line. The temperature of the sensor in turn is coupled to the temperature of the NaK at that point via a 50 second time constant. The T/E pumps are represented by one 8 node T/E pump model containing the heat transfer and fluid dynamic response equivalent to the four parallel pumps. The boilers are also represented by one 5 node boiler model which simulates the 5 parallel boilers in the system. The NaK coolant, related piping and primary loop components are represented by a 30 node heat transfer model which describes the over-all loop.

The study consists of 4 phases; preheat, injection, reactor shutdown, and restart. The preheat phase begins with the initiation of the startup signal and ends when the controller sensor reaches a temperature of 1160°F. Mercury injection begins with the end of preheat and lasts until steady state conditions are reached. The reactor shutdown phase begins with the system operating at steady state condition at which time, the system is arbitrarily shut down for 1 hour. The restart phase is initiated 1 hour after the system has been shut down and continues until 20 KW of electrical power can be generated.

Drum worth, reactivity coefficients, and heat transfer coefficient between the reactor fuel elements and the NaK coolant are those represented in SNAP 2 Reactor-Reflector Specification NR 7550-20. A complete discussion of the SNAP 2 primary loop code may be found in SNAP 2 Startup Analysis, NAA-SR-9078.

Discussion

A. Initial Preheat Results

The preheat phase begins with the initiation of startup at which time the reactor is shut down by -55¢ at an artificial source level of 0.1 watt with 5% NaK flow being maintained in the 40°F isothermal loop. The control drums are initially considered to be 115° from their full in position at this time. This initial 115 degrees setting for the control drums is desired because the drum worth curve for the region from 150 degrees to 115 degrees is essentially flat and contributes only a negligible amount of reactivity to the core and the elimination of the necessity of stepping in this first 35 degrees of drum rotation allows the time required for the preheat phase of startup and restart to be reduced by approximately 30%.

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The startup signal actuates the five control drums which begin stepping in reactivity at a constant stepping rate until the temperature on the boiler inlet reaches 1160°F.

The preheat phase is characterized by the reactor becoming critical and then slightly supercritical until sensible heat generation, with the resulting negative temperature feedback controlling the total core reactivity. Peak reactivity occurs just prior to sensible heat at which time the shortest reactor period is encountered.

Figures 2 through 8 demonstrate the preheat transients for the reference startup case in this study. Reactivity was stepped in at a rate of 1 degree total every 10 seconds for four simultaneously inserted control drums. It may be seen from Figure 7 that the maximum core reactivity occurring just before sensible heat is 42¢. The reactor period at this time is calculated to be 9.23 seconds. This period is calculated over a 10 second interval by means of the following expression.

$$\frac{N}{N_0} = e^{\frac{(t - t_0)}{T}} \quad \text{or} \quad T = \frac{t - t_0}{\ln \log (N/N_0)}$$

where: N = neutron level @ t seconds
N₀ = neutron level @ t₀ seconds
T = reactor period

Starting the reactor up from an initial artificial source level of 0.1 watt as opposed to the spontaneous fission power of 10⁻⁸ watts reduces the peak core reactivity. In a previous startup simulation which began with the 10⁻⁸ watt source, spontaneous fission rate, and utilized the same 1 degree total/10 second stepping rate, the maximum reactivity encountered was found to be 61¢ with a corresponding period of 3.1 seconds.

Just after sensible heat generation, a reactor power spike is encountered which is the most severe power peak in the preheat phase. Figure 6 shows that a maximum peak of 263 KW may be expected. After this initial power spike, smaller power peaks are produced up to the end of the preheat phase. These power spikes are dampened by the NaK flow transients (Figure 4) which are a direct result of the bootstrapping action of the thermoelectric pump. Elimination of the T/E pump in favor of an on-the-shaft pump or an electromagnetic pump operating from an external power source could result in extremely high power transients during preheat if only five to ten percent NaK flow were maintained during this phase of startup.

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Figure 2 shows that the most severe thermal transients for the reactor outlet temperature to be 4°F/second indefinitely and 11°F/second for 30 seconds. This is below the limits of 8 degrees/second for 20 seconds established for the 2/10A reactor.

Another preheat case was run utilizing a stepping rate of 1 degree total every 5 seconds which resulted in transients which were overly severe with respect to the ground rules listed earlier in this report. Figure 11 shows a maximum power spike of 575 KWt and Figure 12 shows a maximum reactivity of 53%. Figure 9 shows that the thermal transients for this case lay within the limits; however, the 1 degree/5 second stepping rate appears to be unacceptable because of the large power transients involved.

The preheat phase of startup ends when the sensor located on the boiler inlet reaches 1160°F. It may be seen from Figure 5, that the temperature at the boiler inlet has reached 1200°F at this time. The temperature difference between the boiler inlet temperature and the sensor is dependent on the thermal response of the sensor and the rate of increase of boiler inlet temperature. A time constant of 50 seconds was used to simulate the thermal response of the sensor in this study. It may also be noted from Figure 4 that the NaK flow has reached 190 lb/min at the end of preheat. This represents approximately 60% of full NaK flow and tends to help damp out the injection transients encountered in the next phase of startup.

B. Injection

The boiler inlet temperature sensor is set to actuate just below the lower deadband temperature set point. This actuation simultaneously initiates mercury flow in the power conversion loop and long term reactor control. The deadband set points used in this study were assumed to be 1180°F to 1210°F; however, later studies may change these points. The long term reactor controller operates only if the boiler inlet temperature goes out of the limits of the deadband and remains out for preset amount of time. Due to the large NaK flow rate in the 20 KWe system, the injection transients are more rapidly damped than in the 3 KW SNAP 2 system.

The injection transients are primarily caused by the sudden heat load placed on the boiler and the increase in NaK flow rate. The sudden heat transfer from the NaK to the mercury in the boiler causes the NaK boiler outlet temperature to decrease rapidly. The reactor thus sees a lower reactor inlet temperature causing reactivity transients due to the negative grid and fuel temperature coefficients. The large temperature difference between the reactor inlet and outlet causes an increased power demand on the reactor. The liquid mercury passing through the T/E pump also cools the cold junction of the pump leading to an increase in NaK flow rate just after injection. The negative temperature coefficient feedback and large power demand on the reactor causes a large power spike soon

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after injection while the 60% NaK flow rate at the end of preheat coupled with the occurrence of the NaK flow peak just after injection tend to suppress this power spike.

Figures 13 through 19 show the primary loop injection transients which are expected if all four mercury systems are started simultaneously. Figure 13 shows that thermal transients should be no problem during injection, although the reactor outlet does peak up to 1250°F for a short period of time. Figure 17, however, shows a 340 KW power spike occurring just after injection. The power transient limitations on the 2/10A reactor are not presently known; however, it is felt that this 340 KW power spike may be detrimental to the reactor.

Problems associated with the simultaneous injection may be eliminated by delaying injection of one or more of the power conversion units until the first large power spike has decayed. Figures 20 through 26 show the resulting transients obtained when three units are injected simultaneously with the fourth unit delayed by three minutes. Figure 20 shows the maximum reactor outlet temperature peaking at 1260°F with the thermal transients well within the limitations of the reactor. Figure 24 shows that the magnitude of the reactor power spike is only 268 KWt for a short period of time. Figure 23 shows the boiler outlet temperature decreasing to only 995°F for a short period of time while Figure 25 demonstrates that a maximum core reactivity of only 24¢ can be expected at injection. The transient experienced approximately 12 minutes after injection is caused by the long term controller removing reactivity in order to put the boiler inlet temperature into the deadband.

The long term controller delay time is governed by the natural period of the system after mercury injection. The system oscillations for the advanced 20 KWe system are quickly dampened by the large NaK flow rate. Due to the shorter period, approximately 2½ to 3 minutes, the delay time for this system may be made significantly shorter than the 400 second delay time required for the SNAP 2 design.

Delaying the injection of mercury units solves the excessive power transients; however, it does add the complication of an injection delay mechanism. However, it may be possible to activate the delayed injection in conjunction with another convenient signal.

Figure 27 shows the expected maximum power peaks if one, two, three or four systems are injected simultaneously. Although the transients shown in this study are for the simultaneous injection of three units with one unit delayed, it is not meant to imply that this delayed injection scheme is recommended. These transients are shown because they will represent the most severe delayed injection transients possible. The simultaneous injection of two units with the other two units delayed will provide less severe transients and will result in the same total startup time. The two and two scheme is presently considered to be the best method if delayed injection is required.

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An alternate means of suppressing the large power spike after mercury injection of all 4 power conversion systems simultaneously would be to provide a still larger NaK flow rate at the end of preheat. This could be accomplished by means of an external radiator attached to the T/E pump which is the case for the newer modular system discussed earlier in the report.

The injection transients appearing in this study are shown through steady state operation; however, startup, as previously defined by the ground rules, is considered to end approximately 3 minutes after the initiation of the last mercury injection signal. The 3 minutes represent the approximate time required before 20 KW electrical power can be supplied to a load. Startup time for the simultaneous injection of all four systems is 28 minutes; 31 minutes are required if one mercury system startup is delayed.

C. Reactor Shutdown

The reactor shutdown phase begins with the system at steady state and simulates the transients expected if the reactor is suddenly scrammed and all mercury flow in the power conversion loop is stopped. After the reactor has scrammed by reflector removal, the control drum would be driven out at the same stepping rate as was used for insertion during preheat. This would assure a significant shutdown condition when the reflector is brought back into place.

The transients seen in Figures 28 through 31 show the effect of shutdown on the primary loop. The NaK flow rate decrease after shutdown may be seen in Figure 29. The NaK flow may be seen to level out at 30 lbs/min (10% of full flow). This is caused by the almost constant temperature decrease of the hot and cold junctions of the T/E pump. It may be concluded from these NaK flow transients that no external power will be required to maintain NaK flow during shutdown. The NaK loop temperature decay seen in Figure 28, is dictated by the radiation heat losses to the reactor shield, R/C cooling rate, and the initial reactor power decay. These heat losses assume that the NaK loop is gold coated with an emissivity of .03. The heat losses have been minimized to maintaining high reactor temperature. This shutdown provides initial conditions for restart after 1 hour which will produce the most severe thermal transients possible.

D. Restart

The reference restart seen in this study is begun 1 hour after the system has been shutdown and is similar to the original preheat phase of startup with the exception of initial conditions. The initial conditions for the restart phase are established by the reactor shutdown transients. The restart signal provides for the

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rapid replacement of the reflector. After the reflector has been repositioned, the control drums, which were stepped back out to their original position, are once again stepped in at a 1 degree total/10 second rate.

The restart transients may be seen in Figures 32 through 38. One may note that the reactor is shut down by $\$2.00$ (Figure 37) at the beginning of this phase. This large shutdown effect (compared to the "cold" value of -55ϕ) is due to the negative temperature coefficients of the grids and fuel. The first portion of the restart phase is characterized by the continued decay of the NaK loop temperatures as the reactor approaches critical. The high NaK temperatures during restart require the addition of more reactivity to reach the point of sensible heat generation by the reactor.

The reactor outlet temperature transients may be seen to be $8^{\circ}\text{F}/\text{second}$ for 40 seconds and $4^{\circ}\text{F}/\text{second}$ indefinitely in Figure 32. These transients are not as severe as those found in the preheat phase and are well within the limits of the 2/10A reactor.

The maximum core reactivity for restart was found to be 40ϕ (Figure 37) and corresponds to a period of 11 seconds. This is primarily due to the fact that the reactor was started up from a 1 watt photoneutron source level. The maximum power transient encountered was found to be 190 KWt (Figure 36). The preheat portion of restart required approximately the same length of time required by the initial preheat. The primary difference being, that for the restart case, there is more time required to reach sensible heat and less time required between sensible heat and mercury injection.

The injection portion of restart was not simulated as the transients would not be significantly different from the previously discussed injection transients. Xenon poisoning is not considered in the analysis of restart because experience with the S2DR reactor, and analytical calculations by the Reactor Engineering Department have found poison transients to be negligible.

Conclusions and Recommendations

This study has resulted in the following conclusions and recommendations for start and restart of the advanced 20 KW mercury Rankine system analyzed here.

Conclusions

1. A safe startup or restart may be completed in a minimum of about 30 minutes with no adverse effects to the system.
2. Flux control of the reactor is not required in order to start the system in less than one hour.

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3. The reactor startup procedures and control developed for the SNAP 2 system may be utilized for the 20 KW system without any major modifications.
4. The large NaK flow rate required for the 20 KWe system dampens the startup transients and provides for a more stable system.
5. No provisions for external power to supply NaK flow rate during shutdown periods of 1 hour or less are necessary.

Recommendations

1. An artificial source be established for the initial startup.
2. A stepping rate of 1 degree total/10 seconds be set for the control drums during the preheat portions of startup and restart.
3. A delayed method of mercury injection be adopted unless it can be determined that the 2/10A reactor can withstand power transients of 340 KWt for short periods of time.

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ADVANCED 20 KW. POWER SYSTEM

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INJECTION TANKS

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PRIMARY LOOP PREHEAT TRANSIENTS

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PRIMARY LOOP PREHEAT TRANSIENTS

FIGURE #3

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PRIMARY LOOP PREHEAT TRANSIENTS

NAK FLOWRATE IN PRIMARY LOOP AND BOILER LBS/MIN

FIGURE # 4

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PRIMARY LOOP PREHEAT TRANSIENTS

FIGURE # 5

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PRIMARY LOOP PREHEAT TRANSIENTS

FIGURE # 6

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PRIMARY LOOP PREHEAT TRANSIENTS

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PRIMARY LOOP PREHEAT TRANSIENTS

FIGURE #8

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PRIMARY LOOP PREHEAT TRANSIENTS

FIGURE # 9

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PRIMARY LOOP PREHEAT TRANSIENTS

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PRIMARY LOOP PREHEAT TRANSIENTS

stepping rate = 1 degree / 5 seconds

FIGURE # 11

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PRIMARY LOOP PREHEAT TRANSIENTS

TOTAL REACTIVITY IN DOLLARS

FIGURE #12

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PRIMARY LOOP INJECTION TRANSIENTS

SIMULTANEOUS INJECTION

REACTOR INLET AND OUTLET TEMP. (F)

FIGURE #13

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PRIMARY LOOP INJECTION TRANSIENTS

SIMULTANEOUS INJECTION

FIGURE #14

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PRIMARY LOOP INJECTION TRANSIENTS

FIGURE #15

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PRIMARY LOOP INJECTION TRANSIENTS

FIGURE #16

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7353-86 L
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PRIMARY LOOP INJECTION TRANSIENTS

FIGURE #19

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PRIMARY LOOP INJECTION TRANSIENTS

DELAYED INJECTION

@ time = 0, 3 Mercury Systems are injected
@ time = 3 min the 4th Mercury system is injected

REACTOR INLET AND OUTLET TEMP. (F)

FIGURE #20

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PRIMARY LOOP INJECTION TRANSIENTS

FIGURE #2.

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PRIMARY LOOP INJECTION TRANSIENTS

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PRIMARY LOOP INJECTION TRANSIENTS

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PRIMARY LOOP INJECTION TRANSIENTS

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7353-16 L
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PRIMARY LOOP INJECTION TRANSIENTS

DELAYED INJECTION

@ time = 0, 3 Mercury systems are injected

@ time = 3 min the 4th Mercury system is injected

FIGURE # 25

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PRIMARY LOOP INJECTION TRANSIENTS

DELAYED INJECTION

@ Time = 0, 3 Mercury systems are injected

@ Time = 3 min, the 4th Mercury system is injected

CONTROLLER TEMP. SENSOR (F)

TIME FROM INJECTION IN MINUTES

FIGURE # 24

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FIGURE #27

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7353-97 L
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REACTOR SHUTDOWN TRANSIENTS

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7393-97
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REACTOR SHUTDOWN TRANSIENTS

FIGURE #29

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7393-97 L
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REACTOR SHUTDOWN TRANSIENTS

FIGURE #30

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7353-97 L
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REACTOR SHUTDOWN TRANSIENTS

FIGURE # 31

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7355-01 L
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RESTART TRANSIENTS

FIGURE #32

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7383-01 L
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RESTART TRANSIENTS

FIGURE #83

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7593-01
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RESTART TRANSIENTS

NAK FLOWRATE IN PRIMARY LOOP AND T/E PUMP LBS/MIN

FIGURE # 34

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7333-01 L
004 000

RESTART TRANSIENTS

FIGURE # 35

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7303-01 L
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RESTART TRANSIENTS

FIGURE #36

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RESTART TRANSIENTS

FIGURE # 37

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RESTART TRANSIENTS

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Page 50 P&I DIAGRAM
20 KW SYSTEM

BLANKENSTEIN 1-20-64

REVISED 3-12-64

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