Conf-921110--18

BNL-47769
INFORMAL REPORT

BNL--47769

DE92 019254

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July 1992

Paper submitted to the Third Internal
Symposium on Power Plant Transients
Anaheim, California
November 8-13, 1992

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This work is performed under the auspices of the United States Department of Energy under contract No. DE-AC02-76CH00016.

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ABSTRACT

This paper describes the simulation of asymmetric loss of flow events in Russian designed VVER-1000 reactors using the RETRAN-02 Mod4 computer code. VVER-1000 reactors have significant differences from United States pressurized water reactors including multi-level emergency response systems and plant operation at reduced power levels with one or more main circulation pumps inoperable. The results of these simulations are compared to similar analyses done by the designers for the Rovno plant.

INTRODUCTION

Asymmetric loss of flow events have been simulated for the Russian designed VVER 1000. This is a four loop pressurized water reactor with a nominal power of 1000 MWe. In VVERs, the unit may be run with one or more pumps shut down. The reactor power is reduced to a specified level consistent with a power to flow ratio of one for the number of operating pumps (e.g., if three out of four pumps were operating, the power level would be set at 75% of full power). This specified reduced power is also affected by the symmetry of the stopped loops. In the case of two stopped pumps, if the loops are not opposite each other, the reactor would be scrammed. Thus, there are several different initial conditions for loss of flow events.

The main production model of the VVER-1000 is the model V320. Currently, there are nine model V320s operating in the former Soviet Union, two in Bulgaria, and one in Hungary. The four primary loops of the VVER-1000 model V320 consist of a horizontal steam generator and a main circulation pump. The loops are arranged symmetrically around the reactor vessel. Earlier VVER-1000 models (there are five units operational in the former Soviet Union) contained loop isolation valves that allowed the flow in a non-operating loop to be greatly reduced. The fuel pins are housed in an open hexagonal lattice and the control assemblies have no fuel followers. Unlike earlier VVER designs, all VVER-1000s have a full emergency core cooling system, consisting of four passive accumulators (two inject directly into the vessel downcomer and two inject into the vessel upper plenum) and three independent high and low pressure injection pump trains.

Events simulated include:the loss of power to one pump,with failure to reduce power;the startup of a pump in a loop from 75% power; and multiple pump failures from different initial conditions. The results of these transients are compared to results generated for the safety analyses report for the Rovno plant(U.S.D.O.E.,1989 a), a model V320 plant that went operational in 1987.

SUMMARY DESCRIPTION OF VVERS

There are two principal sizes of VVERs producing about 440 Mwe and 1000 Mwe, called the VVER-440 and VVER-1000, respectively. There are two principal models of the VVER-440s, denoted as the models V230 and V213. The current production model of the VVER-100 is designated V320. There were two earlier models: the prototype model V187 and the first production model, the V302, of which four were built. There are also currently two advanced VVER-1000s being designed, the VVER-88 and the VVER-92, which contain additional safety related features to prevent and mitigate the effects of accidents.

A total of 16 VVER-440 model V230s went into operation between 1971 and 1980; six in the former Soviet Union and ten in Eastern European countries. At least two of these, located in Armenia, have been permanently shut down. Fifteen VVER-440 model V213s are operational, with an additional nine units under construction. There are ten VVER-1000s operational and approximately twenty under construction. Several VVER-1000 projects have been canceled or deferred. Additionally, there are two specialized VVER-440s, designated the model V318, under construction in Cuba.

The VVER-1000 model V320 has four primary loops, consisting of a horizontal steam generator and a shaft-sealed main circulation pump (Figure 1). The main circulation pumps are of the centrifugal type, with flywheels to provide extended coastdown times during power outages. The earlier model VVER-1000s, the V187 and the V302s, also have loop isolation valves. The loop isolation valves are normally used in two instances: 1) If the pump is not operating in that loop, but the plant is (VVERs are allowed to operate at a reduced power level with up to half the pumps not operating), the loop isolation valve in the hot leg will be closed to reduce back flow in that loop; 2) the loop isolation valves are also closed during planned shutdown periods to permit maintenance on the steam generators. Unlike VVER-440s, all VVER-1000s have a full capacity shutdown heat removal system. Therefore, for economic reasons the loop isolation valves were not part of the design of the later model V320.

The fuel pins are housed in an open hexagonal lattice, which permits cross flows. The fuel is UO_2 in annular pellet form, clad in a zirconium-niobium alloy, arranged in a triangular lattice, and housed in 312-rod rectangular ducts.Control rod arrays without fuel followers are used. There is an emergency core cooling system, consisting of four accumulators, three high pressure injection pumps, and three low pressure injection pumps. VVER-1000s are housed in steel lined, cylindrical, prestressed concrete containment vessels.

VVER-1000s have three levels of emergency response depending upon sensor indications of fault severity. This type of protection system, involving two levels of response less drastic than a full scram, is one factor contributing to the generally excellent VVER performance records. The highest level, AZ-1, is equivalent to a scram in U.S. plants. The control rods are inserted into the reactor at maximum speed. Simultaneously, other plant protection systems, such as emergency diesel generators, are brought on line. Less than half the pumps running generates a scram signal. At the next level, called emergency action AZ-2, the control rods are inserted into the core at maximum speed in groups, but if the warning signal stops, the insertion stops. Loss of power to less than half the main circulation pumps generates an AZ-2 response. Should an AZ-2 warning signal persist for a specified period following initiation of the AZ-2 response, the protection system will upgrade the signal to a full scram,AZ-1. The last emergency response level, AZ-3 inhibits the withdrawal of control and safety rods from the core. Control rod insertion is permitted. When the initiating signal disappears, upward movement is allowed. Core exit temperatures and pressures greater than specified limits generate AZ-3 signals.

A complete description of VVERs, with listings of power plant locations and their status, is given in U.S.D.O.E., (1987).

VVER COMPUTER SIMULATION MODELS

The Electric Power Research Institute (EPRI) developed code, RETRAN-02 Mod 4 (J.H. McFadden et al, 1984), was used to simulate four loss of flow events in three different VVER models. The RETRAN code has been used extensively since 1978 and is considered to be generally applicable to large and small break loss of coolant accidents, one dimensional pressurized water reactor transients, and anticipated transients without scram. Features of the RETRAN code used to model VVER reactors are discussed here. Full details on the RETRAN code models are contained in McFadden et al, 1984.

RETRAN uses a one-dimensional, homogeneous equilibrium mixture thermal hydraulic model for the reactor cooling system. The VVER models were limited to the main components of the primary coolant system. The pressurizer was modeled using a nonequilibrium option. The sprays and heaters were modeled, as were the pressurizer relief valves, using control logic listed in U.S.D.O.E., 1987 and U.S.D.O.E., 1989a. The heat transfer library included two-phase natural convection heat transfer correlations. Point kinetics was used to model the reactor neutronics. The reactivity feedback coefficients were weighted on a local basis axially for each core channel modeled. The horizontal steam generators were modeled as single average tube heat exchangers with the secondary side temperature and flow rate specified.

The VVER-1000 model V320 nodalization is shown in Figure 2. In this two loop model, one loop models the lumped effect of three loops. The pressurizer spray line is not shown in Figure 2. Elevations, volumes, and component specifications were taken from

U.S.D.O.E., (1987) and U.S.D.O.E., (1989a) and Sartmadjiev(1988). In this nodalization, one hot fuel channel, one average fuel channel, and one average control channel were represented in the core region. The control assembly channels do not differ substantially from the fuel channels as reactivity control is maintained using borated steel pins which are inserted into locations within fixed fuel assemblies. In a normal fuel assembly, fixed burnable poison pins occupy the same locations as the control pins. Additionally, the VVER-1000 fuel assemblies are open permitting cross flow between core channels. Cross flow effects were not modeled, however. The core channels were modeled with four axial locations, the lower three nodes being heated and the topmost node being unheated. A chopped cosine distribution was used to determine the axial power profile.

TRANSIENT RESULTS

Seizure of a Single Pump

A loss of a single main circulation pump was simulated for a VVER-1000 model V320 (rated at 1000 Mwe) using the RETRAN code. As a single failure, the reactor power was kept at full power (3300 MWth),instead of being reduced to 75%. The designers believe this accident to be more severe than the stoppage of a pump when only two or three pumps are running. In their analysis of this event reported in U.S.D.O.E. (1989 a), the fuel cladding temperature was reported to have increased to 1100°F.The MDNBR was reported to be lower than 1.05.

In the RETRAN simulation,the flow in the loop with the stopped pump reversed quickly after the pump seizure at 0.1 seconds (Figure 3). The core flow was reduced to approximately 70% of full flow conditions, due to the flow bypassing the core and entering the loop with the stopped pump(Figure 4). With the reduction of core flow, the core inlet temperature starts to rise(Figure 5). The fuel clad surface temperature in the hot channel increased only slightly by approximately 15°F,reaching a peak far below that predicted by the designers(Figure 6). The MDNBR dropped from 2.2 at steady state to 2.0 at the end of the simulation. The less severe nature of the RETRAN simulation transient is directly due to the assumptions made on the hot channel conditions. Most significantly, the designers assumed an uncertainty factor of 1.16, while the RETRAN analysis used a best estimate values. Additionally, the RETRAN analysis specifically modeled the hot channel so that the effects of flow redistribution,although small, are noticeable. The designers calculation kept the fractional flow rate through the hot channel constant throughout the calculation.

A primary/secondary power imbalance exists in this transient and the primary temperatures will continue to rise without operator intervention.

Startup of a Single Pump at 75% Power

When the primary coolant pump of a loop which has not been operating is activated, the temperature in the coolant flowing into the core decreases due to the introduction of cold fluid from the previously inactive loop. As in US reactors, VVERs have a negative moderator temperature coefficient over most of their cycle. (At the very beginning of a core cycle, the moderator temperature coefficient is usually positive because of the presence of relatively large amounts of boron.) Therefore, the decrease of the coolant temperature caused by the pump startup leads to an increase in the reactor power

In US pressurized water reactors, this event is analyzed only at startup conditions for extremely low power levels, since operation at power with a pump out of service is prohibited. In VVER-1000s, the plant can be at significant power levels with one or two pumps out of service. Moreover, VVER-1000s usually do not contain loop isolation valves,like the VVER-440, which can be partially closed to significantly reduce the flow rate, and hence the reactivity effect, of a pump startup.

The transient simulated in this paper involved the startup of a pump in a plant near the end-of-cycle, when the reactivity effect would be greatest, operating at 75% of full power with three pumps running. Normally, the plant would be operated at 67% of full power with three pumps running to provide an extra safety margin, but operation at the 75% level is permitted. The initial condition for the plant was determined by tripping a pump, allowing the flow rates to reach equilibrium, and then adjusting the power levels, pressures, and core inlet and outlet temperatures to correspond to the operating values specified in U.S.D.O.E. (1989a). The pump in the inactive loop was then started, with a 10 second time assumed for it to reach full operating speed.

The flow rate in the previously inactive loop increases in response to the pump startup (Figure 7). There is also a small decrease in the flow rate in the active loops because of the new pressure distribution in the primary loop(Figure 8). The flows very quickly reach new equilibrium values. The temperature in the core inlet starts to decrease as the colder water in the previously inactive loop is injected into the core (Figure 9). This colder water causes the overall reactivity in the core to increase, through the increase in the coolant reactivity(Figure 10). The power in the reactor increases until the other reactivity feedback mechanisms allow a new equilibrium power level to be reached (Figure 11). The power increase leads to an increase in the clad temperature(Figure 12), but the rise is small due to the increased core flow rate.

Loss of All Pumps at 75% Power and 100% Power

The loss of all operating pumps is considered to be a low probability event because of the presence of multiple power systems, including backup diesel generators. In this event, the reactor is tripped when power is lost to two or more of the operating pumps. The AZ-1 signal (scram) is on a two second delay. In the analyses of this event done for the Rovno plant (U.S.D.O.E.,1989a), no significant effects were predicted and the plant was predicted to be cooled by natural circulation.

Two separate events were simulated using the RETRAN code. In the first case, the plant was assumed to be at 100% power with all four pumps running. In the second event, the plant was at 75% power, with only three pumps running and back flow in the loop with the inoperative pump. The designers consider the 100% power event to be an umbrella transient, with results predicted to be more severe than for the 75% power case.

In these simulations, long term natural circulation was established in both cases. In the 75% power case, the flow in the loop with the inactive pump changed from a negative to a positive flow, even though the heat sink from the steam generator was extremely minor (Figure 13). The flows in the powered loops in both cases decreased gradually, reflecting the long pump coastdown times of the flywheels on the centrifugal pumps(Figures 14 and 15). The flow rates in the hot channel reflected the pump coastdown, and eventually reached a new steady state with small positive values of flow. The fuel clad temperature rises in both cases were small,with the 100% power case reaching slightly higher temperatures.

SUMMARY AND CONCLUSION

Asymmetric loss of flow events have been simulated for the Russian designed VVER 1000. In general, the results obtained using the RETRAN code where in general agreement with the limited information prepared for the safety analysis report for the Rovno plant. These results indicate no severe problems exist for the VVER-1000 when operating with less than all four pumps operating. However, the RETRAN code is one-dimensional in nature and streaming effects in which slugs of cold or hot water are not completely mixed before entering the core region can not be analyzed fully. Multi-dimensional analysis are required to fully demonstrate the safety of VVER-1000s in these regimes.

ACKNOWLEDGEMENTS

Parts of this work were performed under the auspices of the US Department of Energy, Office of International Programs of the Assistant Secretary for Nuclear Energy.

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Figure Captions

Figure 1--	Schematic Drawing of the Primary Heat Transport System of the VVER-1000
Figure 2--	RETRAN Nodalization of the Primary Heat Transport System of the VVER-1000
Figure 3--	Flow Rate in the Loop with Seized Pump
Figure 4--	Core Inlet Flow Rate with Seized Pumps
Figure 5--	Core Inlet Temperature with Seized Pump
Figure 6--	Hot Channel Clad Temperature with Seized Pump
Figure 7--	Flow Rate in the Loop with Restarted Pump
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Figure 11--	Normalized Power Level with Restarted Pump
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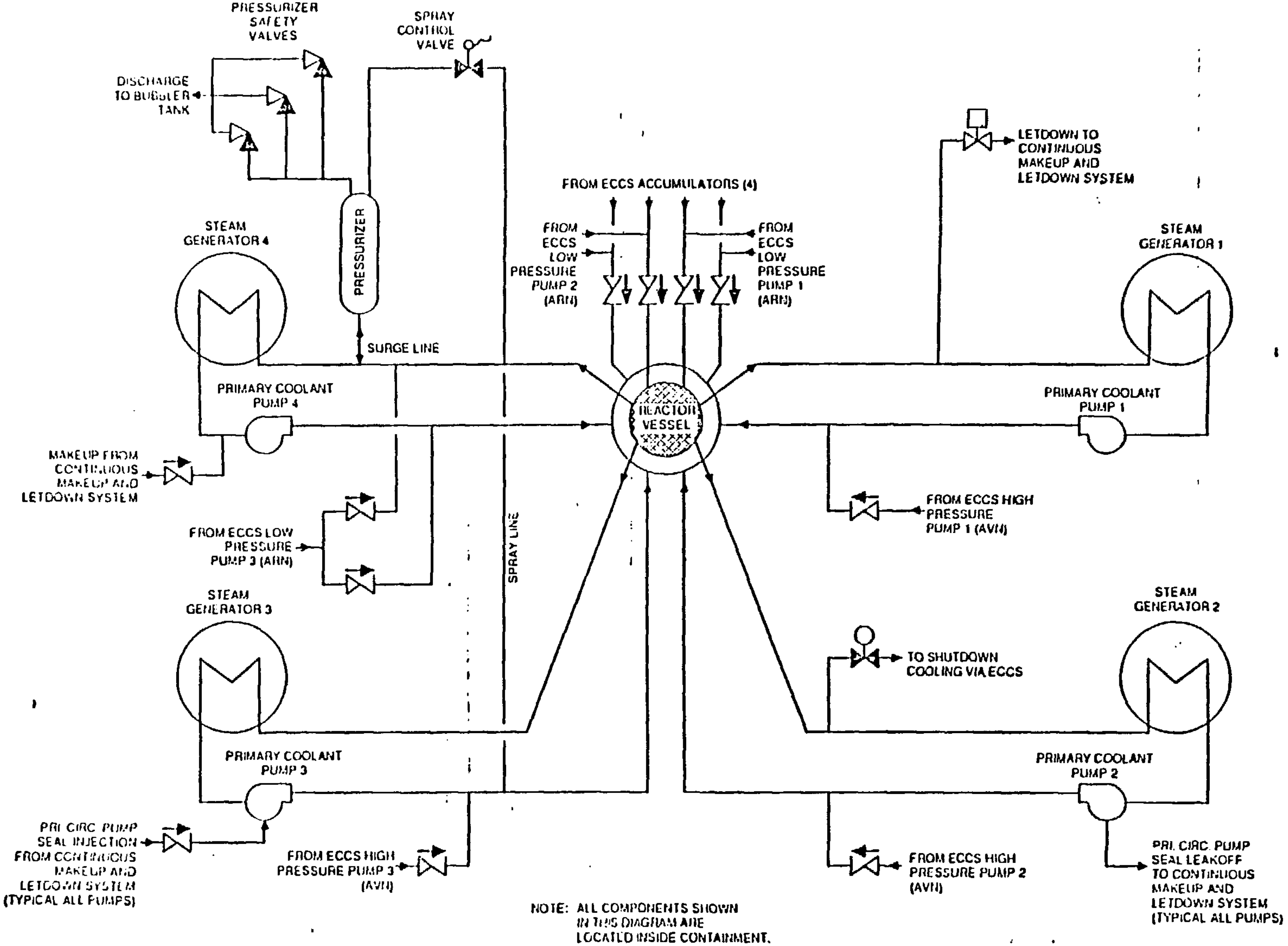
Figure 13--	Flow Rate in the Loop with Inactive Pump at 75% Power
Figure 14--	Flow Rate in Loops with Active Pumps at 75% Power
Figure 15--	Flow Rate in Loops with Active Pumps at 100% Power



NOTE: ALL COMPONENTS SHOWN IN THIS DIAGRAM ARE LOCATED INSIDE CONTAINMENT.

Figure 1-- Schematic Drawing of the Primary Heat Transport System of the VVER-1000

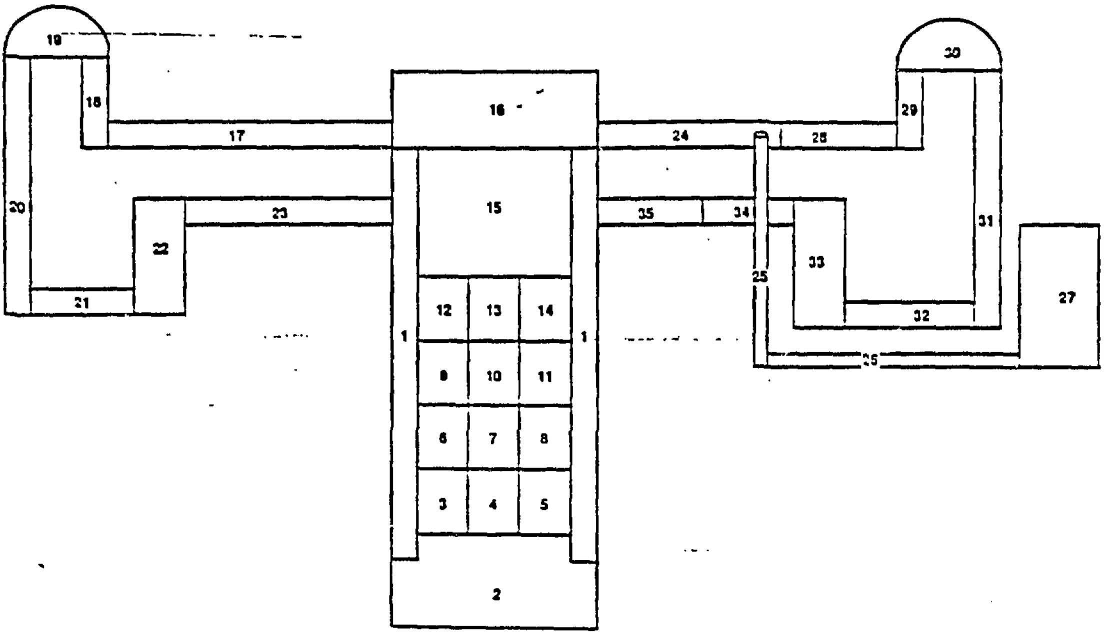


Figure 2-- RETRAN Nodalization of the Primary Heat Transport System of the VVER-1000

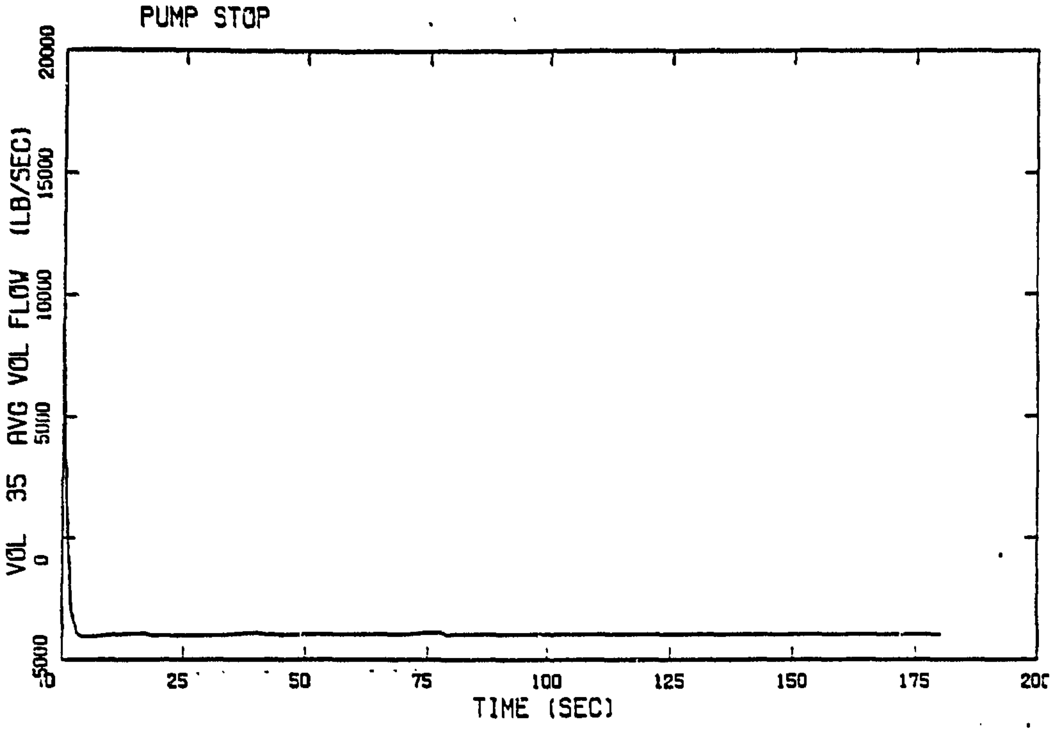


Figure 3-- Flow Rate in the Loop with Seized Pump

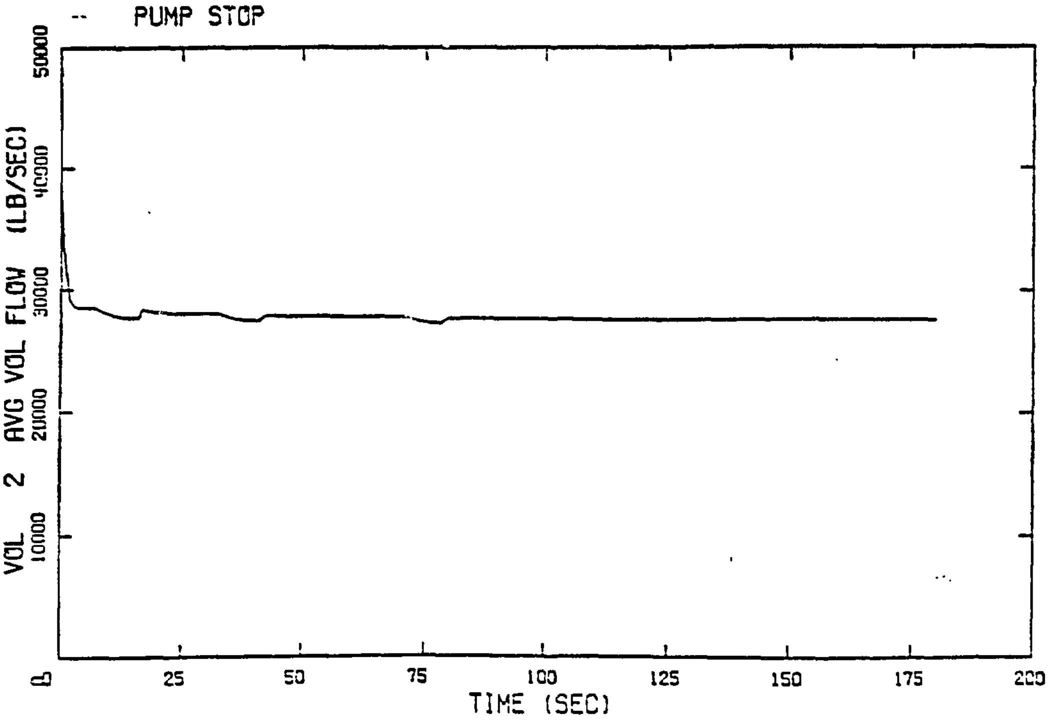


Figure 4-- Core Inlet Flow Rate with Seized Pumps

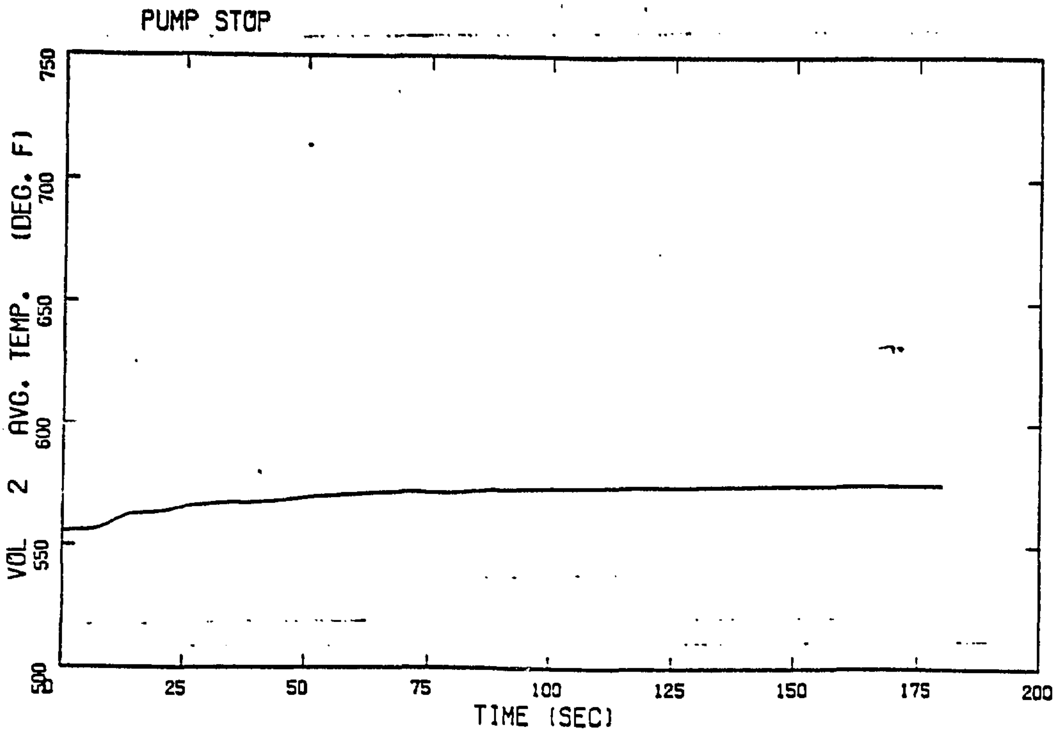


Figure 5-- Core Inlet Temperature with Seized Pump

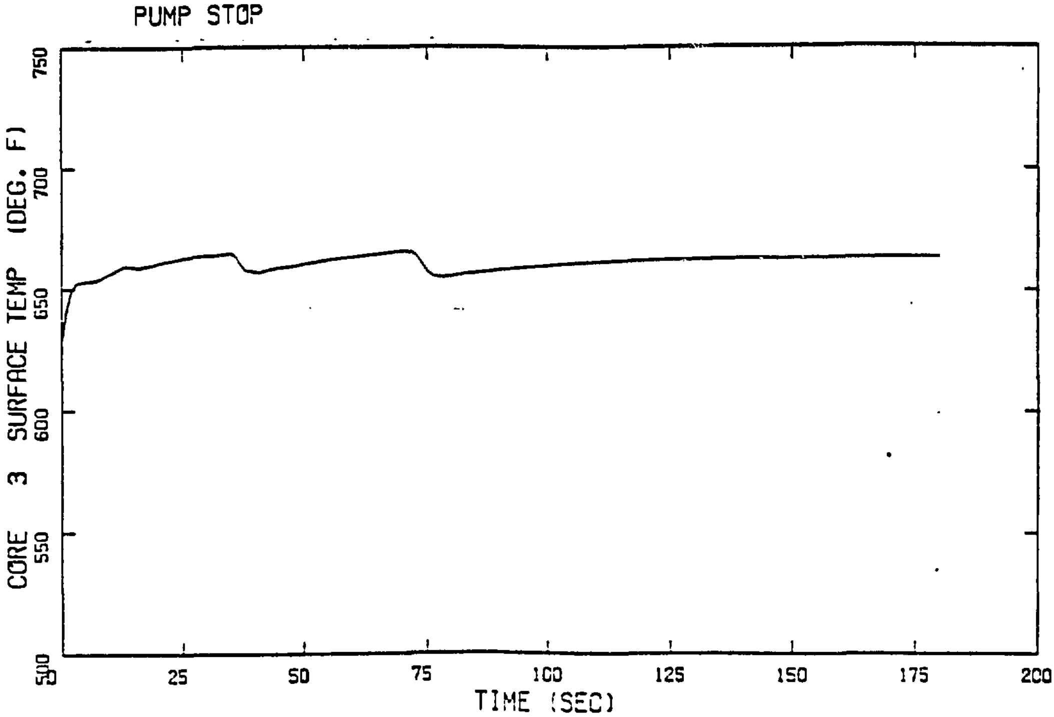


Figure 6-- Hot Channel Clad Temperature with Seized Pump

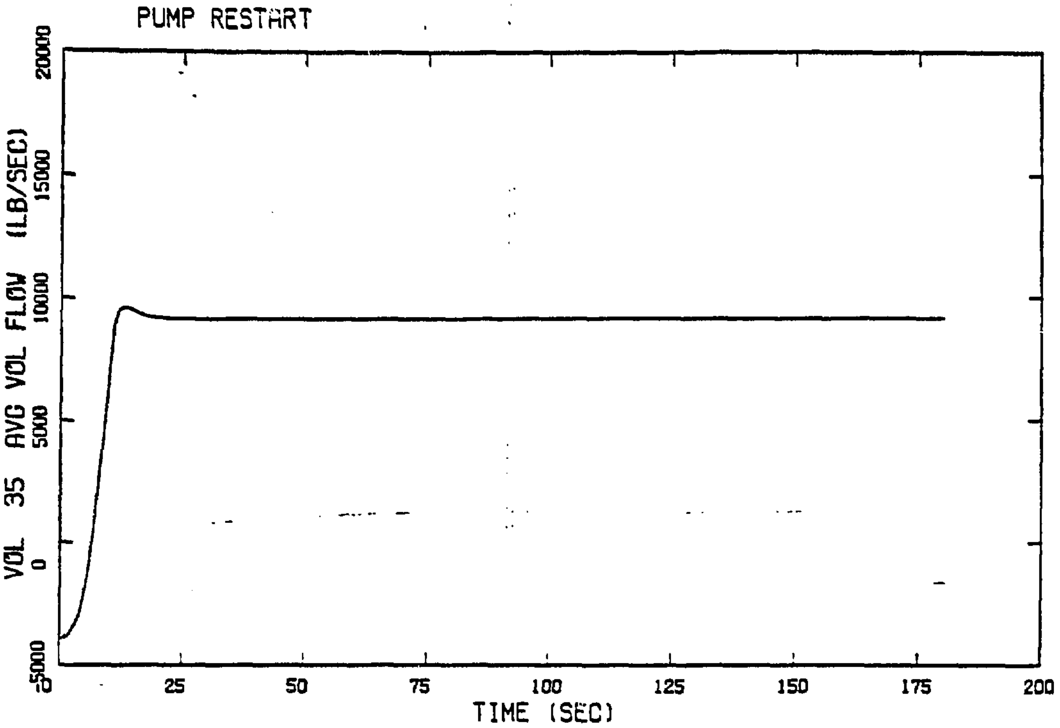


Figure 7-- Flow Rate in the Loop with Restarted Pump

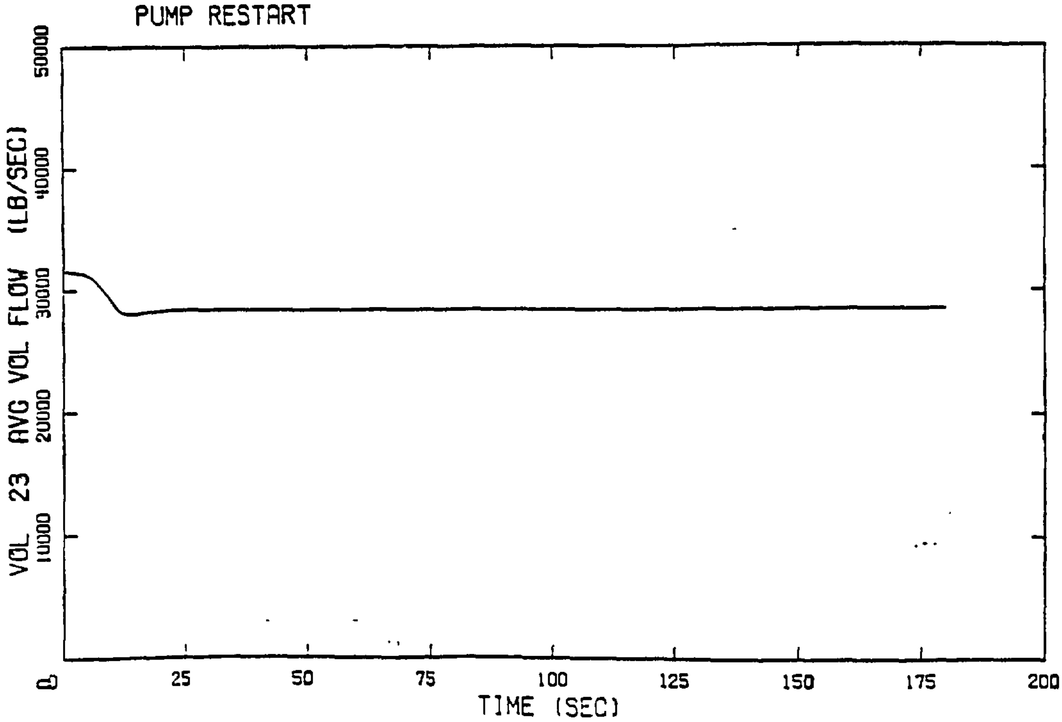


Figure 8-- Flow Rate in Loops with Active Pumps

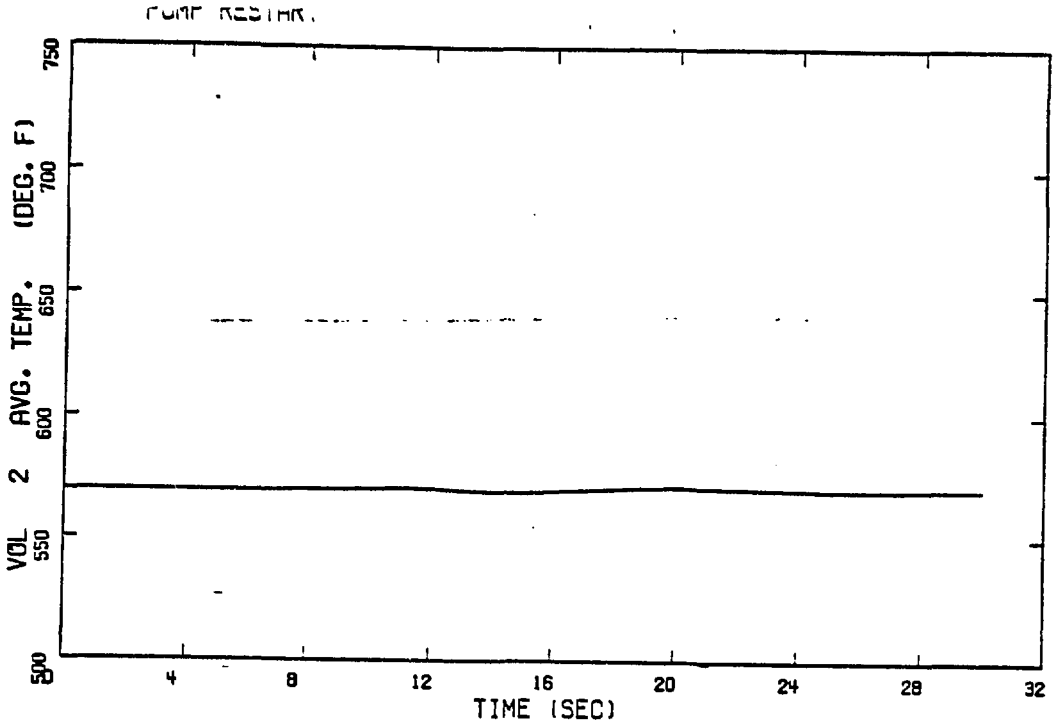


Figure 9-- Core Inlet Temperature with Restarted Pump

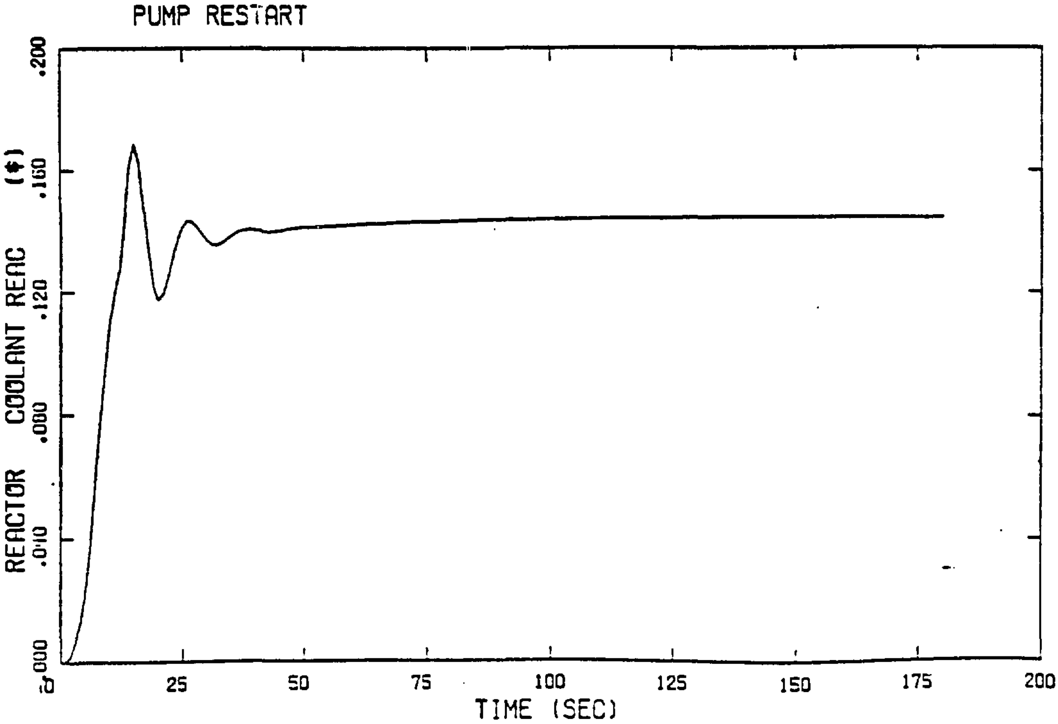


Figure 10-- Reactivity Effects with Restarted Pump

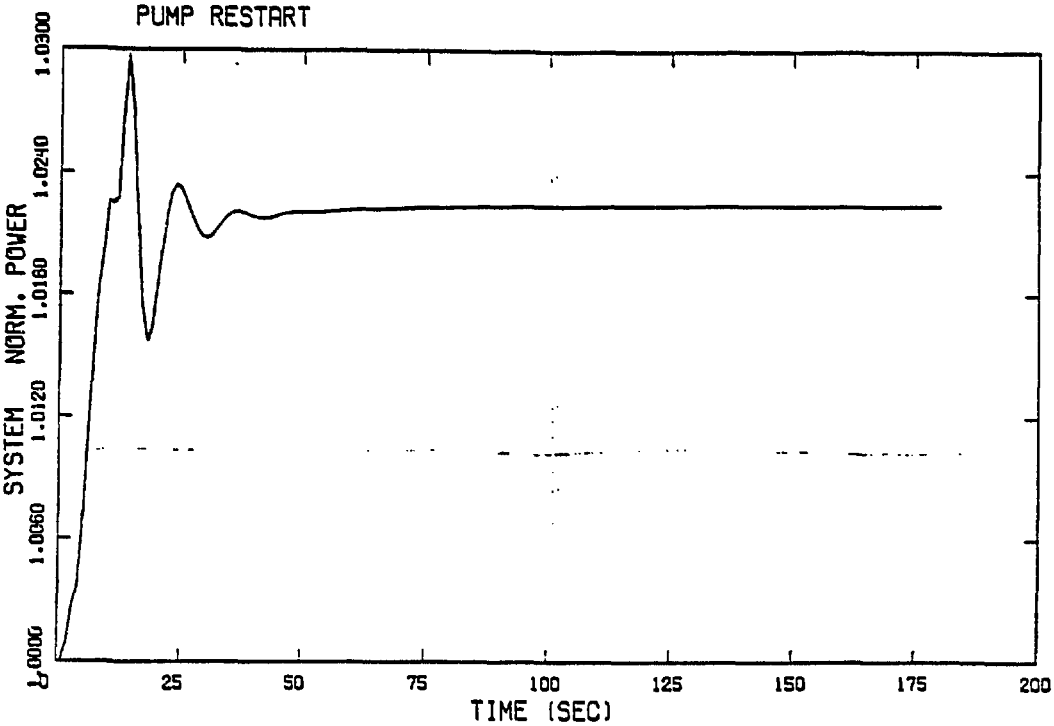


Figure 11-- Normalized Power Level with Restarted Pump

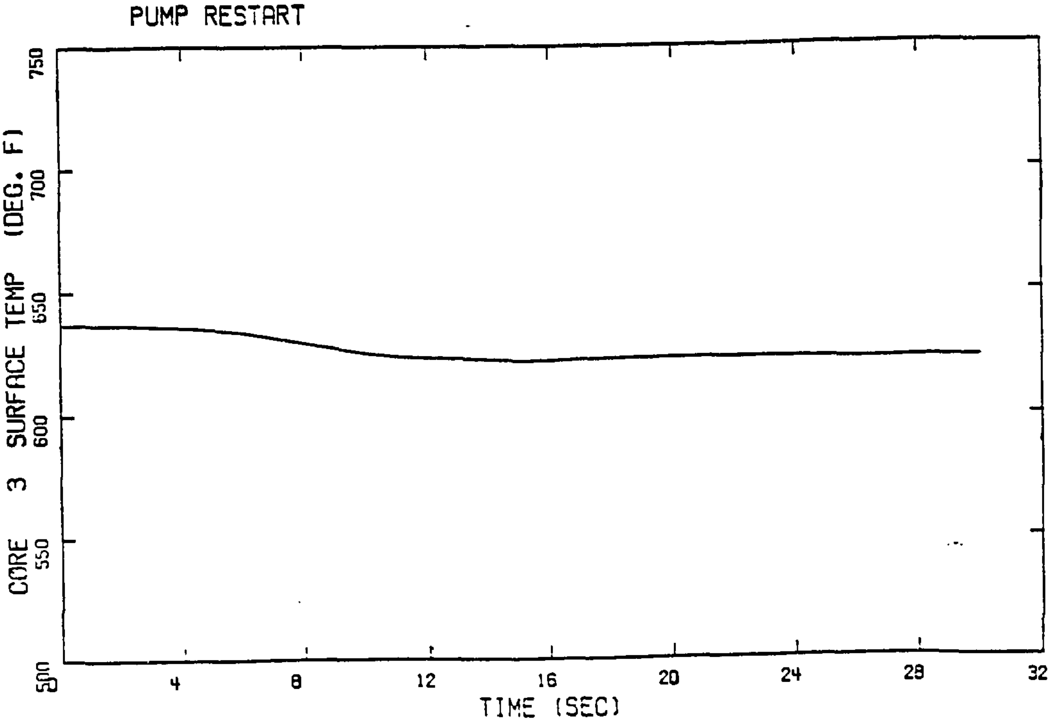


Figure 12-- Hot Channel Clad Temperature with Restarted Pump

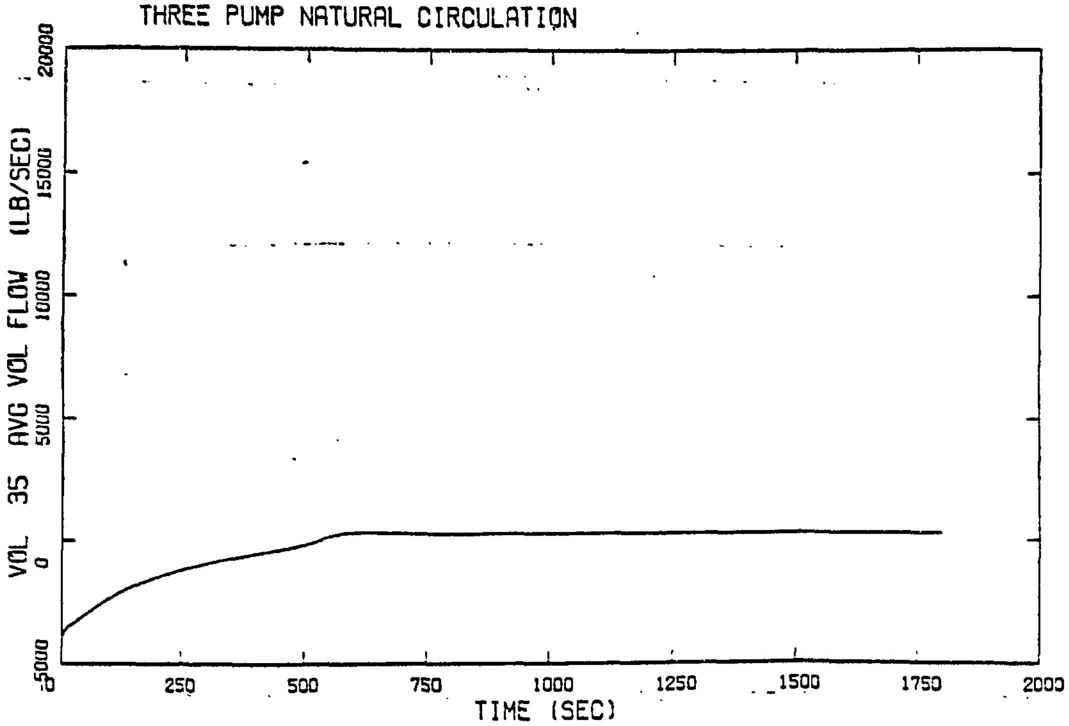


Figure 13-- Flow Rate in the Loop with Inactive Pump at 75% Power

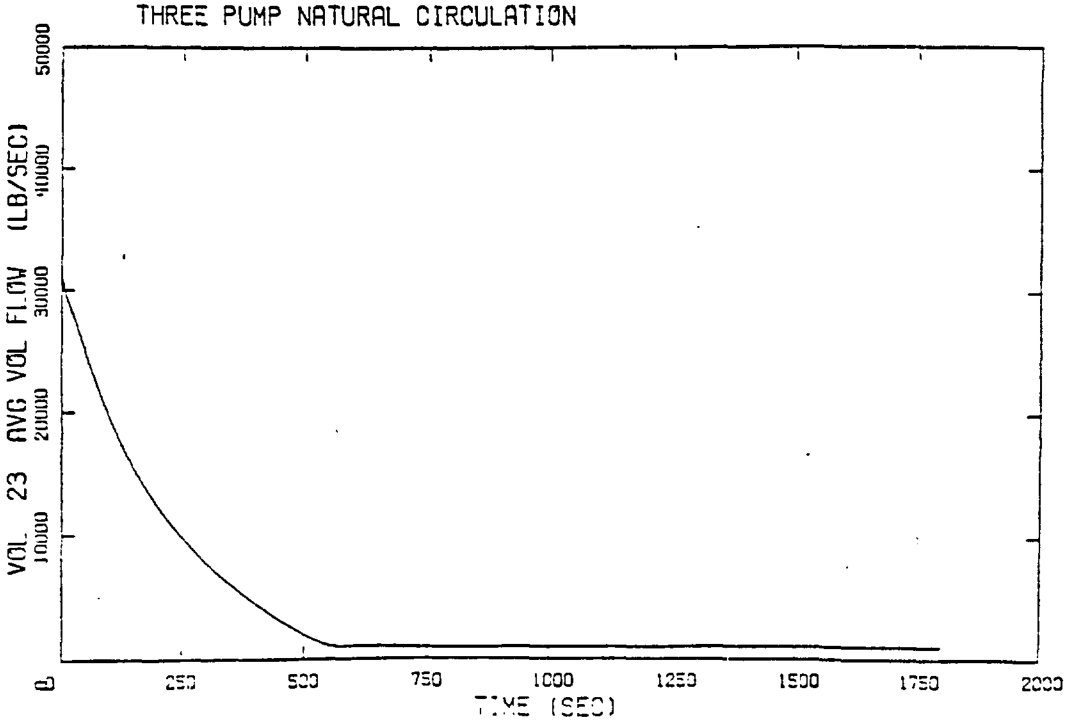


Figure 14-- Flow Rate in Loops with Active Pumps at 75% Power

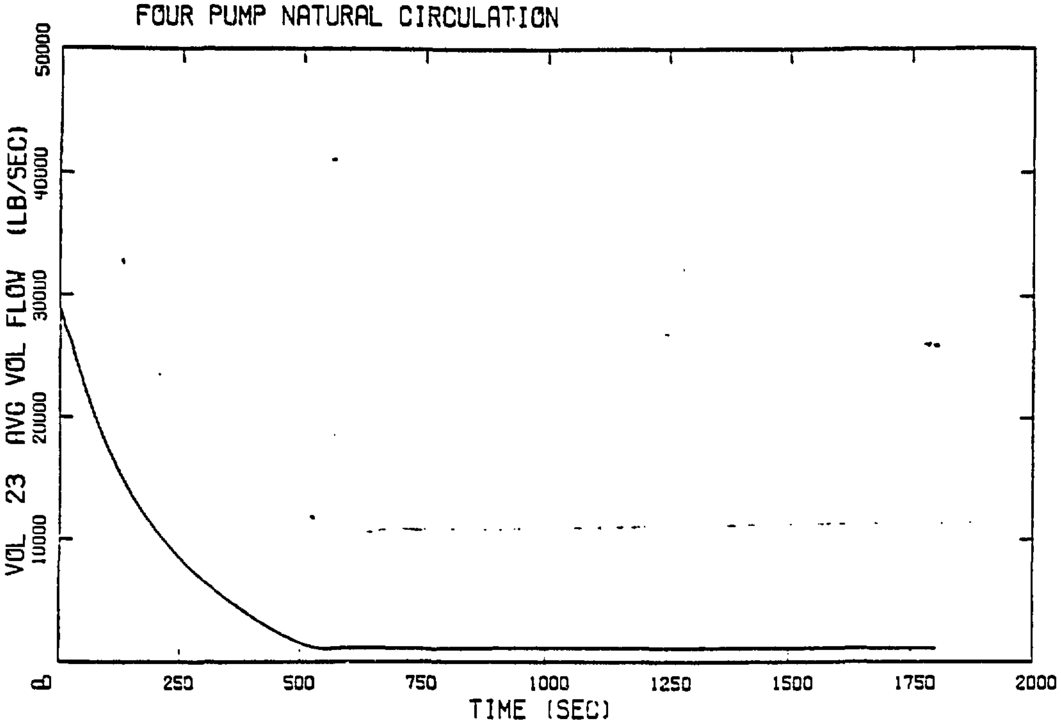


Figure 15-- Flow Rate in Loops with Active Pumps at 100% Power