Natural Circulation Performance of the AFR-300 Advanced Fast Reactor

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Abstract - *The AFR-300, Advanced Fast Reactor (300 Mwe), has been proposed as a Generation IV concept. It could also be used to dispose of surplus weapons grade plutonium or as an actinide burner for transmutation of high level radioactive waste. AFR-300 uses metallic fuel and sodium coolant. The design of AFR-300 takes account of the successful design and operation of EBR-II, but the AFR-300 design includes a number of advances such as an advanced fuel cycle, inspectability and improved economics. One significant difference between AFR-300 and EBR-II is that AFR-300 is considerably larger. Another significant difference is that AFR-300 has no auxiliary EM pump in the primary loop to guarantee positive core flow when the main primary pumps are shut down. Thus, one question that has come up in connection with the AFR-300 design is whether natural circulation flow is sufficient to prevent damage to the core if the primary pumps fail. Insufficient natural circulation flow through the core could result in high cladding temperatures and cladding failure due to eutectic penetration of the cladding by the metal fuel. The rate of eutectic penetration of the cladding is strongly temperature dependent, so cladding failure depends on how hot the cladding gets and how long it is at elevated temperatures. To investigate the adequacy of natural circulation flow, a number of pump failure transients and a number of design options have been analyzed with the SASSYS-1 systems analysis code. This code has been validated for natural circulation behavior by analysis of Shutdown Heat Removal Tests performed in EBR-II. The AFR-300 design includes flywheels on the primary pumps to extend the pump coastdown times, and the size of the flywheels can be picked to give optimum coastdown times. One series of transients that has been run consists of protected loss-of-flow transients with various values for the combined moment of inertia of the pump, the motor and the flywheel giving coastdown times from 70 seconds to 586 seconds. In this transient series both the main pump motors and the pony motors lose power. Another series of loss-of-flow cases involved staggered failures of the pony motors. The main pump motors fail, the reactor scrams, and the pumps coast down to pony motor speed. Then at various times the pony motors are assumed to fail. If the pony motors fail at the wrong time, then the resulting transient can be more severe than if the pony motors failed at the same time as the main motors. A third series of cases involved a reactor scram followed by failure of both the main pump motors and the pony motors at various times. For all of these cases, satisfactory natural circulation behaviour can be obtained if the right design options are used..*

I. INTRODUCTION

One of the goals in the design of the AFR-300 reactor is to provide for passive safety. Among other things, this means that loss of electric power and loss of pumps must be accommodated without damage to the reactor. The purpose of the work reported here is to determine whether natural circulation flow is adequate if the pumps fail. The primary pumps have both main motors and battery driven pony motors. The pony motors provide 5-6% of nominal flow. This flow is quite adequate for shut-down heat removal. Natural circulation only comes into effect if both the main pumps and the pony motors fail, so this is a very low probability event.

Heat removal in the intermediate heat exchanger (IHX) enhances natural circulation. On the other hand, in order to reduce construction costs the steam generators in this design are not considered to be safety grade. Therefore, in the calculations reported here no credit is taken for operation of the steam generators during the transients; and coolant flow in the intermediate loops is shut off at the beginning of the transients.

Passive safety often also includes shut-down of the reactor power to decay heat levels by negative reactivity feedback in incidents where the control rods fail to scram. While this is an important aspect of passive safety, such cases are not included in this work; in all cases considered here the control rods are assumed to scram properly.

II. THE AFR-300 REACTOR

Figure 1 shows the current design for the AFR-300 primary

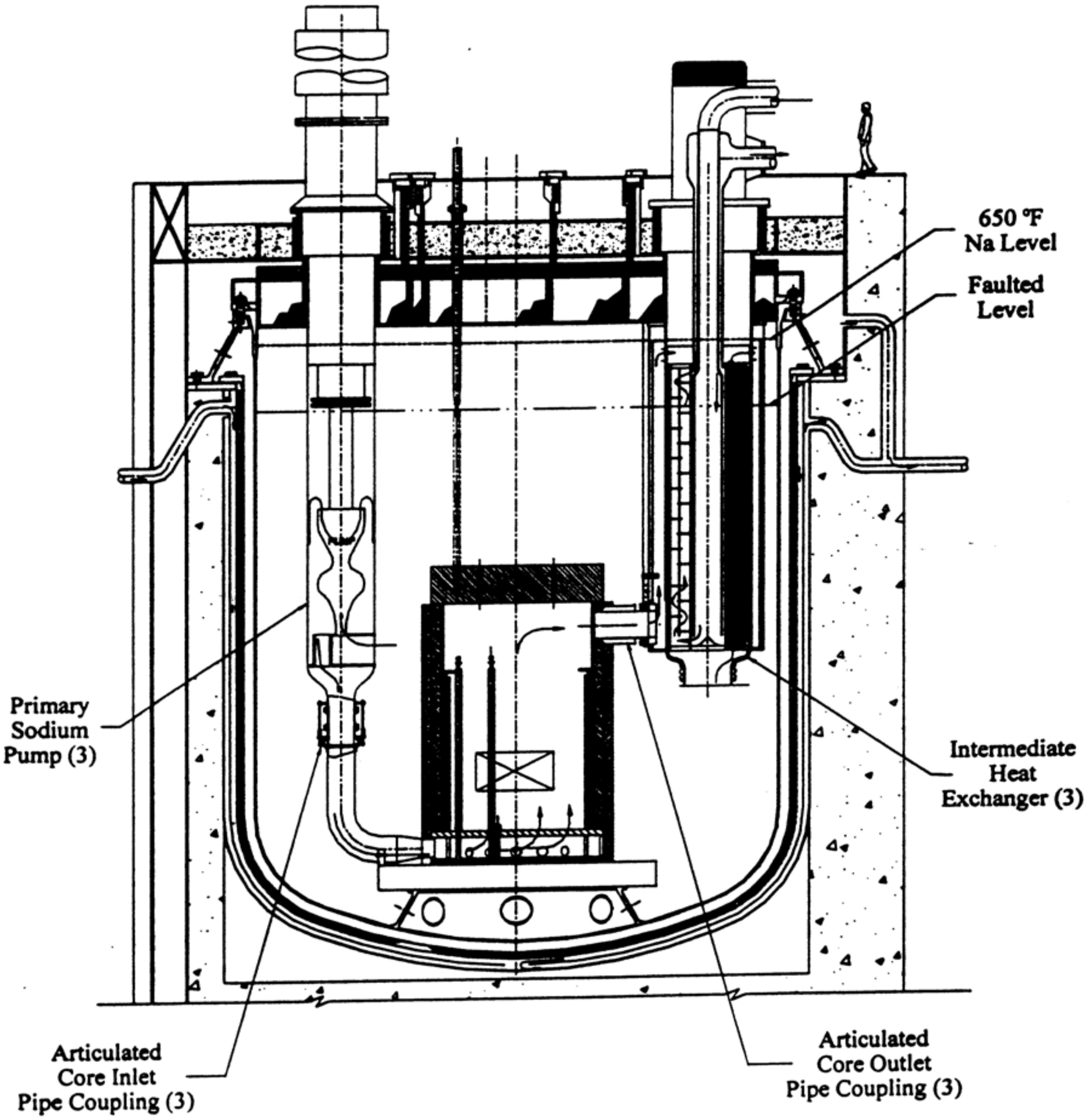

Figure 1, AFR-300 Primary System

vessel and many of the components in it. This design has a closed outlet plenum and a large cold pool. There are three primary pumps and three intermediate heat exchangers. In order to provide low impedance to primary flow under natural circulation conditions the primary flow goes through the tube side of the IHX. Not shown in this figure are the steam generators and the intermediate coolant loop outside of the primary vessel.

The main factor in determining the primary loop natural circulation head if there is no intermediate loop heat removal from the IHX is the elevation difference between the outlet from the IHX and the middle of the core. In the current design this elevation difference is about 2.7 meters.

III. ANALYSIS METHODS

The natural circulation calculations for AFR-300 were carried out with the SASSYS-1 LMR systems analysis code.[1] This code was developed at Argonne National Laboratory. While the code is capable of analyzing a wide range of transients in liquid metal cooled reactors, it was developed mainly for analyzing shutdown heat removal with either forced convection or natural circulation. Analysis of Shutdown Heat Removal Tests[2] in the EBR-II reactor was used to validate[3] the SASSYS-1 code for natural circulation conditions.

The SASSYS-1 code contains neutron kinetics coupled with a detailed thermal hydraulics treatment of the core, the primary and intermediate heat removal loops, and the steam generators. Both steady-state and transient calculations are done by the code. The neutron kinetics treatment contains point kinetics and an optional 3-D time dependent neutron kinetics capability.

The thermal hydraulics in SASSYS-1 uses a multi-channel treatment for core subassemblies. Each channel represents one subassembly or a group of similar subassemblies. A channel models a fuel pin, its associated coolant, and structure. The subassembly duct wall is treated as structure, and wrapper wires around the fuel pins can be included in the structure. Coolant and structure above and below the fuel pin is also treated: the whole length of the subassembly from the inlet plenum to the outlet plenum is modeled. For metal fuel the core channel treatment also includes the DEFORM-5 module to calculate fuel pin failure based on gas plenum pressure and eutectic penetration of the cladding by the metal fuel. The eutectic penetration rate, which is strongly temperature dependent, is calculated using the correlation of Bauer, Fenske, and Kramer.[4] Beyond the core subassemblies the code uses the PRIMAR-4 module to calculate coolant pressures and flows, as well as temperatures for coolant and structure (walls). Calculations are made for inlet and outlet plenums, pipes, pumps, intermediate heat exchangers, and steam generators.

IV. NATURAL CIRCULATION CASES CONSIDERED

Three sets of natural circulation cases are considered in this work. These sets were picked in an attempt to span both the most likely and the most severe natural circulation cases. The first set is a protected loss-of-flow case following failure of the steam generators. At the beginning of the transient the steam generators fail and the intermediate loop coolant flow stops. After 0.25 seconds a scram occurs and the control rods start to drop. The primary pumps start to coast down at the same time as the scram. In this set the pony motors do not work, so natural circulation conditions occur after the pump coast-down. The AFR-300 design includes flywheels on the primary pumps to extend the coast-down time. The size of the flywheels has not been set yet, so a number of cases were run for different values of the total moment of inertia of the pump, motor and flywheel. These values give coast-down times of 68 , 150, 300 and 586 seconds. The second set of cases consists of staggered pony motor failures. These cases start the same as the first set, but the pony motors work for a while and maintain the primary pumps at a low speed. Then at various times the pony motors failed. Running the pony motors for a while tends to destroy part of the natural circulation head, so when the pony motors eventually fail the transient is more severe than if the pony motors did not run at all. The third set of cases consists of staggered failures of both the main pump motors and the pony motors. In this set the pumps do not trip when the control rods scram. Instead the pumps fail some time later and the pony motors do not run. This set tends to give the most severe natural circulation transients.

For the first set of transients a five channel core treatment is used. Table 1 describes these five channels. For this set of cases a detailed many channel core model is not needed. The peak transient temperatures will occur in hottest channel, so the hottest channel must be represented. In addition, the average channel is needed to provide the correct total coolant flow and heat to the primary loop. The reflectors, shields, and control rod subassemblies are represented even though they contribute little to the results. The peak channel is 20% hotter than the average channel. This 20% is not based on detailed evaluation of hot channel factors. No such evaluation has been done for this design. Previous experience with EBR-II, FFTF and CRBR indicates that 20% is in the right range. This subject will have to be revisited when the design is more mature, but changing the hot channel factor to 25% or 30% would not change the conclusions for this set of transients.

Table 1, 5 Channel Model for Protected LOF Cases

channel	description	power/ sa (Mw)	flow/sa (kg/s)	relative p/f
1	peak driver	10.86	41.11	1.20
2	average driver	8.227	37.34	1.00
3	reflector	.04113	1.494	.125
4	shield	.01645	.3733	.200
5	control rods	.2468	2.241	.500

For the staggered pump failure cases the 18 channel model described in Table 2 is used. More core detail is needed for the staggered failure cases than in the first set of cases because in the staggered failure cases the hottest transient results often do not occur in the subassembly with the hottest normal operation temperatures. The hottest subassembly has more natural circulation gravity head and therefore more coolant flow when the pumps stop. The worst transient temperatures are often in a cooler subassembly that has little gravity head when the pumps stop. In order to set up the 18 channel case, it was necessary to use detailed neutronics data for the power in each subassembly. The powers at the beginning of an equilibrium cycle were used. The final flow orificing scheme for the reactor is yet to be determined. For these calculations a preliminary scheme was used. The flow was orificed by subassembly ring, based on the average ring power at the beginning and end of an equilibrium cycle. The flow was orificed to give the same average coolant outlet temperature for each ring.

All cases reported here used the PRIMAR-4 model shown in Figure 2. Two loops are modeled. One loop models one real loop. The other computational loop models

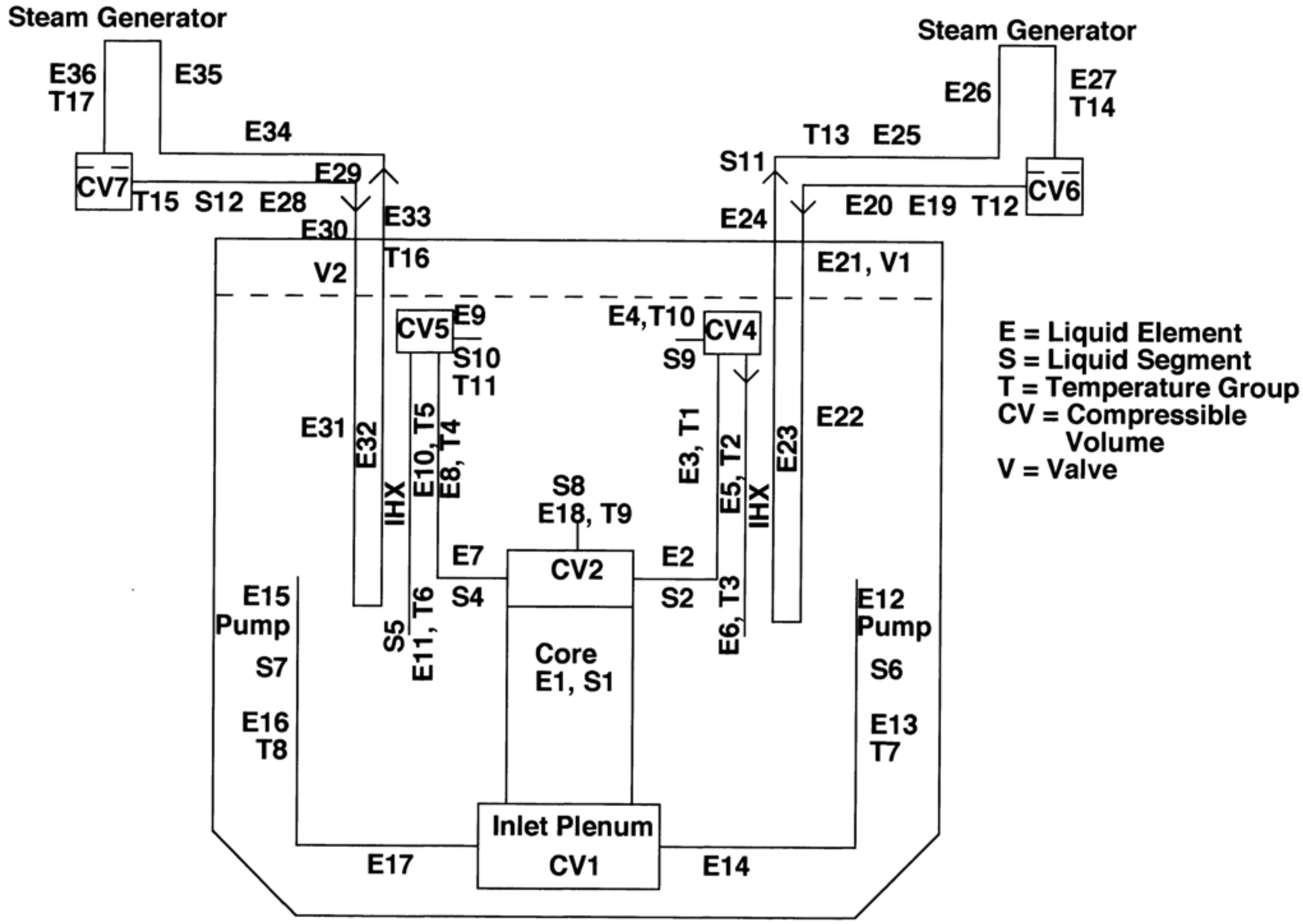

Figure 2, PRIMAR-4 Model of AFR-300

Table 2, 18 Channel Model for Staggered Pump Failures

channel	description	power/ sa (Mw)	flow/sa (kg/s)	power/ flow
1	ring 1 reflector	.09152	.4475	.970
2	ring 2 driver	8.914	42.49	.995
3	ring 3 driver	8.750	41.68	.996
4	ring 4 driver	8.407	39.65	1.006
5	ring 4 driver	8.200	39.65	.981
6	ring 5 driver	7.867	37.32	1.000
7	ring 6 driver	8.563	39.32	1.033
8	ring 6 driver	8.258	39.32	.996
9	ring 7 driver	7.412	31.33	1.122
10	ring 7 driver	6.865	31.33	1.039
11	ring 7 driver	6.069	31.33	.919
12	ring 3 control	.01702	.08303	.973
13	ring 5 control	.00907	.04414	.975
14	ring 8 reflector	.05270	.2552	.981
15	ring 9 reflector	.04076	.1972	.981
16	ring 10 reflector	.02040	.09857	.982
17	ring 10 shield	.04663	.2252	.982
18	ring 11 shield	.02352	.1135	.983

the other two real loops. This PRIMAR-4 model allows for the analyzing asymmetric transients such as the loss of one pump while the other two pumps continue to operate. For all of the transients reported here only symmetric cases were run; the input for both loops was identical. Table 3 describes the liquid elements used in this model. In all cases at the beginning of the transient the temperature drop on the sodium side of the steam generators was set to zero, and the valves in elements 21 and 30 were shut to cut off intermediate loop flow. The steady-state reactor power for all cases was 800 Mwt, the inlet temperature was 616.5 K (650 F), and the mixed mean outlet temperature was 783.2 K (950 F).

V. RESULTS

The power and flow following a scram and pump trip are shown in Figure 3 for a 587 second coast-down. The power drops rapidly after the control rod scram, whereas the flow drops much more slowly, leading to initial overcooling

Table 3, Liquid Elements Used in the PRIMAR-4 Model

element	meaning
1	core channels
2	pipe, outlet plenum to IHX shroud
3	IHX shroud
4	leakage, IHX shroud to cold pool
5	tube side of IHX
6	IHX outlet section
7-11	same as elements 2-6
12	primary pump
13,14	pipes, pump to inlet plenum
15-17	same as elements 12-14
18	Leakage, outlet plenum to cold pool
19	intermediate pump
20	intermediate piping
21	valve
22	pipe
23	shell side of IHX
24-26	intermediate piping
27	steam generator
28-36	same as elements 19-27

of the core. The perturbation in the flow at about 587 seconds is caused by the stoppage of the pump rotor.

The coolant temperatures for this transient are shown in Fig. 4. The core temperatures and the outlet plenum temperature drop initially because the power drops more rapidly than the coolant flow. Then the core temperatures rise to a peak when the pump rotors stop turning. In this calculation there is no heat removal from the primary system during the transient. Most of the heat ends up in the cold pool, causing the rise in the cold pool temperature. The AFR-300 design includes shutdown coolers to remove decay heat if the steam generators are not working, but the shutdown coolers are not currently included in the PRIMAR-4 model. In the current design the shut-down coolers are capable of removing about 0.5% of nominal power. Thus, the shut-down coolers would not make much difference in the first 10,000 seconds of the transient; and they would make a negligible difference in the peak temperatures which occur at about 600 seconds.

The peak cladding temperatures for this transient are shown in Fig. 5. During normal operation the peak cladding temperature in the peak driver subassembly is about 40 K higher than in the average driver., but during the transient this difference drops to less than 10 K. The 650 C limit shown on this figure is a steady-state normal operation limit. Above this temperature eutectic penetration of the cladding can occur at a rate that is highly temperature dependent.

The protected loss-of-steam-generator and loss-of-flow case was run for a number of values of the combined moment of inertia of the pump, motor and flywheel, giving different coast-down times. Peak cladding temperatures for these cases are shown in Figure 6. The 68 second coast-down requires either a small fly-wheel or no fly-wheel. The 300 second coast-down is similar to that of the Phoenix reactor. The 600 second coast-down would require a very large fly-wheel. Thus the cases shown in this figure span the range of likely coast-down times. The highest cladding

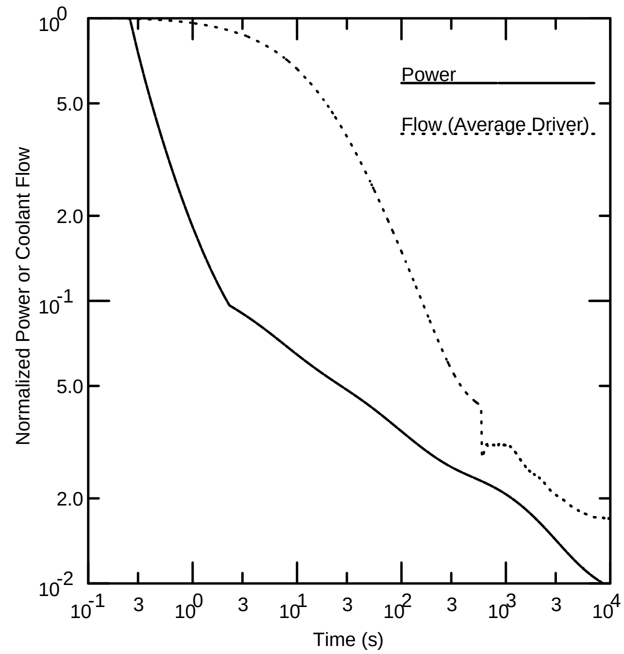

Fig. 3, Power and Flow Following a Loss of Steam Generators and a Pump Trip, 587 s Coastdown

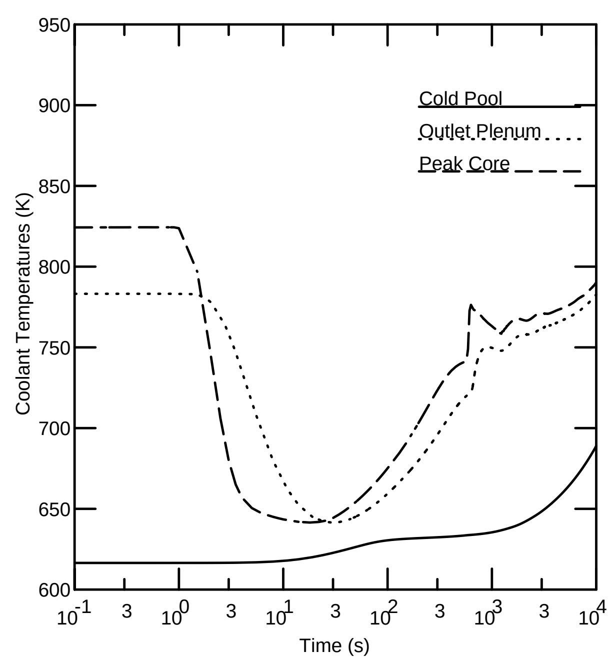

Fig. 4, Coolant Temperatures for a Protected 587 Second Coast-down

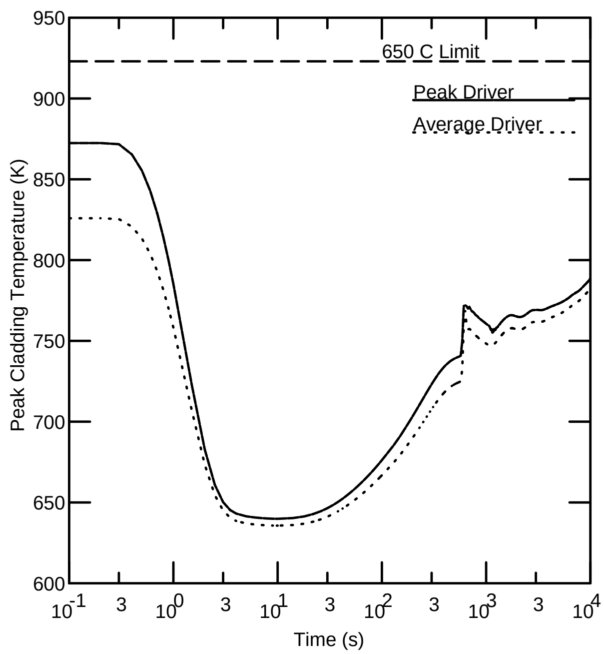

Fig. 5, Peak Cladding Temperatures for a Protected 587 Second Coast-Down

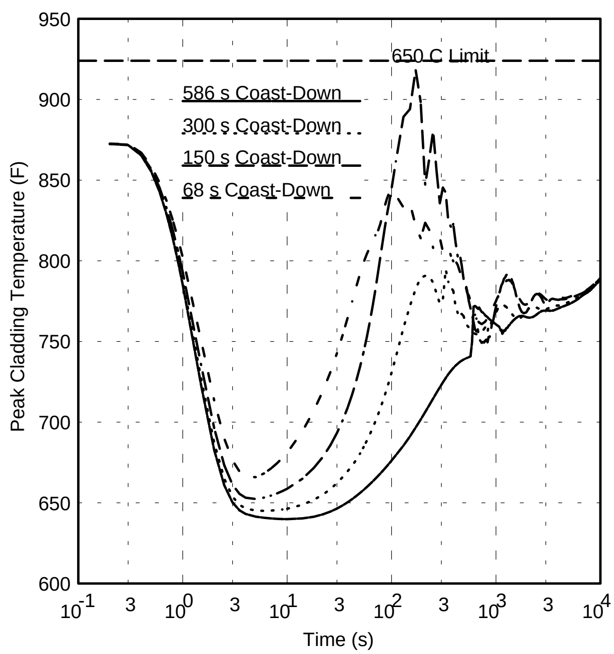

Fig. 6, Protected LOF Peak Cladding Temperatures for Various Coast-Down Times

temperature occurs for a coast-down time of 150 seconds. This is because with this coast-down time as the pumps coast down the primary loop gravity head is reduced. When the pumps stop the reduced gravity head leads to a temporary flow reduction and higher temperatures. For a shorter coast-down time there is less reduction in the gravity head before the pumps stop. For a longer coast-down time the gravity head partially recovers before the pumps stop.

The peak cladding temperatures for a staggered pony motor failure case are shown in Figure 7. This case was a 68 second coast-down with the pony motors failing at 162 seconds. Results for no pony motor operation are also shown for comparison. Note that the initial cladding temperatures are different for the two curves because the no pony motor operation case was for a peak channel, whereas the staggered failure case was for a lower power channel. This was the most severe staggered pony motor case for the 68 second coast-down. In the staggered failure case cladding temperatures reached much higher values than if the pony motors failed at the beginning of the transient. The coolant and cladding heated up almost to the coolant boiling temperature. The cladding temperature was above the 650 C eutectic penetration limit for about a minute, but the fuel pins would still survive with little damage to the cladding.

Figure 8 shows the results for a staggered failure of both the main pump motors and the pony motors. This case was also for a 68 second coast-down. The pumps failed 20 seconds after the control rod scram. In this case coolant boiling occurred in channel 10 for over a minute. The onset of boiling stopped the rapid cladding temperature rise and held temperatures almost constant at the coolant saturation temperature until enough natural circulation gravity heat was established to increase coolant flow rates and decrease temperatures.

With the temperature history shown in Figure 8 there would be significant damage to the cladding and the case for survival of the pins without cladding failure is marginal.

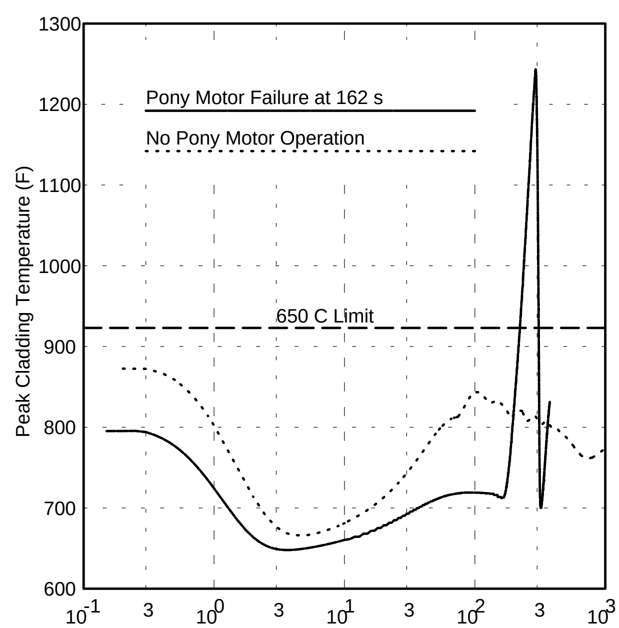

Fig. 7, Peak Cladding Temperatures in channel 11 for a Staggered Pony Motor Failure

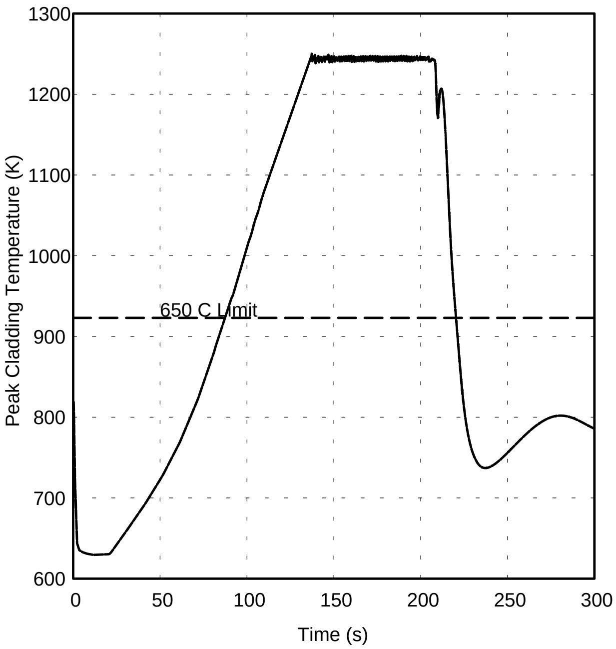

Fig. 8, Peak Cladding Temperatures in Channel 10 for Staggered Failure of Both the Main Pump Motors and the Pony Motors

Using the eutectic penetration rate of reference 4, at the boiling temperature the eutectic would be calculated to penetrate completely through the cladding in 4-5 minutes. Also, the HT-9 cladding is not nearly as strong at boiling temperatures as at normal operating temperatures, and the cladding stress due to internal gas pressure would rise as eutectic penetration reduces the effective thickness of the cladding. The combination of eutectic penetration and stress rupture would lead to failure of the cladding in maximum burn-up subassemblies after about two minutes at the coolant boiling temperature. For lower burn-up the pins might survive for 3-4 minutes. There is considerable uncertainty in the estimates of pin survival time at boiling temperatures because no eutectic penetration rate data has been measured for the high plutonium content metal fuels that AFR-300 would use. The correlation in reference 4 is based on uranium fuel and U-Pu fuel with a low concentration of plutonium.

Staggered pump failure cases were also run for the 300 second coast-down design option. A large number of cases were run spanning a wide range of failure times for staggered pony motor failures and for staggered failures of both the main pump motors and the pony motors. In all cases the transient peak cladding temperatures were lower than the normal operating temperatures. Thus, high peak temperatures due to staggered pump failures can be eliminated by using sufficiently large fly wheels on the pumps.

VI. CONCLUSIONS

For protected transients the natural circulation performance of AFR-300 is adequate if the proper design choice is made for the pump coast-down time. For the normal protected LOF transients a moderate size for the pump fly wheels, giving a coast-down time of about 150 seconds, gives higher peak transient temperatures than either a smaller fly wheel or a larger fly wheel; but over the whole range of coast-down times considered here the temperatures for this transient were not high enough to cause any damage to the fuel pins. For staggered pump failure transients high cladding temperatures and significant damage to the cladding were calculated in some cases with a coast-down time of 68 seconds. For a 300 second coast-down time staggered pump failures did not lead to high transient temperatures.

VII. FUTURE WORK

Future work is needed in two additional areas related to the natural circulation studies reported here. One additional area is unprotected transients and the question of whether negative reactivity feedback is adequate to shut the reactor down without damage if the control rods do not scram. The other additional area is long term shut-down heat removal and the question of whether the shut-down coolers are adequate.

ACKNOWLEDGMENTS

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