8. An Operators View of Reliability Testing and Decay Heat Rejection Systems

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INTRODUCTION

1. The object of this paper is to review the in-situ testing of DHR systems, and to convey policy rather than to indicate a definitive test programme. The test policy is aimed primarily at commissioning the plant and secondly at providing such support for reliability predictions as is practical. Provisions for removal of decay heat from the core and from the reactor tank are described in papers by Broadley and Davies.

SCOPE OF TESTS

2. Tests can be placed in 4 categories according to the objective viz tests designed to demonstrate that

a. the quality of construction is as specified and that the plant as constructed will

b. function as designed

c. perform up to the design specification and

d. be as reliable as predicted.

During construction and commissioning, quality control tests (e.g., pressure and leak tests, weld radiography etc.,) are performed on every appropriate item in safety related systems. Also during this phase every safety related system (and sometimes separate items) is subjected to conventional functional and performance tests with the possible unique exception of inherent safety "systems" such as natural circulation, to which reference will be made later.

FUNCTIONAL TESTING

3. Functional tests are performed on individual items (e.g., motors, batteries etc.,) wherever possible, but are always followed by functional tests on complete systems. These tests may have to be repeated several times to allow coverage of all means of initiation e.g., the operation of the air dampers and fans on the thermal syphon loops can be initiated locally or from the Main Control Room, or automatically from loss of normal electrical supplies. On each test a check is made to confirm that all items of plant have operated, with special attention to redundant items.

4. Whether one or several tests have to be made for the above reasons, it is policy to repeat the tests for "shake-down" reasons i.e., to allow faults arising from poor construction or grossly inadequate design to emerge and be rectified. The number of tests required for "shake-down" is a matter of judgement tempered by practicability, but 3 to 10 would be typical.

5. Normally these "shake-down" tests will be performed as soon as the construction of the system is completed, and this can mean that normal operating conditions are not available. Further repetition of shake-down tests may be required later.

PERFORMANCE TESTING

6. Performance tests are required to ensure that designed capacities have been achieved.

7. Repetition of such tests and measurements are not normally required, but it may be necessary to conduct a series of performance measurements to cover a range of conditions e.g., primary pool temperature. Thus the measurements required for DHR via the PFR thermal syphon loops are

i. the heat rejection of each loop with dampers open and fans off for primary sodium temperature in the range 300 to 580°C

ii. as (i) above with fans on providing forced air circulation

iii. loop start-up times for (i) and (ii)

iv. the forced flow through the core with only one pony motor running, and

v. the natural circulation performance of the core over a range of decay heat levels.

RELIABILITY TESTING

8. Strictly, every test performed makes a contribution towards establishing the reliability of the item or system under test. However where high reliability is required, as is generally the case with DHR systems, a few tests will make a trivial contribution towards demonstrating the achievement of the reliability objective. Thus it is useful to draw a distinction between shake-down tests and prolonged repetitive testing aimed at demonstrating a maximum value of failure probability to a specific confidence level, by calling only the latter type Reliability Testing.

9. Reliability testing is not conventionally included in construction/commissioning programmes. The reasons are obvious and well known. Reliability data are only sought when low failure probabilities are required, and hence confirmation would require very large numbers of tests e.g., using the poisson approximation to binomial sampling distribution, it is necessary to carry out 300 successful tests to substantiate a probability of failure per demand of 10^{-2} at an upper confidence level of 95%.

10. Quite apart from the questionable validity of using the results of repeated tests over a comparatively short time, to provide a failure probability which can be applied over the life of the plant, there will be practical difficulties in conducting the required number of tests on installed plant if a high reliability has to be demonstrated viz

a. too much of the expected life-time of the components on test, or of a component which can not be dis-associated may be required, and serious delays to the overall plant commissioning can occur, especially if the tests can not be kept isolated from other plant conditions.

11. Some plant items can be excepted from these difficulties, the notable example being instrumentation although this normally means artificial injection of signals. However, DHR plant will seldom if ever be free from those difficulties. At PFR, confirmation of reliability predictions by the repeat testing technique alone, has not been contemplated for DHR or DHR-related plant. The only exception to that is the auto-starting system for the diesel engines which maintain the guaranteed electrical supply for "essential" plant including pony motors and thermal syphon fans.

12. Routine testing during the life of the plant is established practice, and should gradually raise the confidence level associated with the target reliability of each system. For a totally untried system the confidence level starts at zero and the build-up with time will be as shown in figure 1. The data is the same for a constant value of the ratio of Target Probability over Test Interval (P/T) and the results of a range of values of this ratio is given.

13. PFR starts with predicted reliability levels obtained from knowledge of the failure frequencies of similar items in other stations and other industries, estimates of repair times needed and specifications of test frequencies. As yet, no acceptable technique has been established for attributing a confidence level to these predictions, but clearly it is well above zero. If and when such a technique is available, that level of confidence becomes the starting point and will be gradually increased over the years by a modest accumulation of tests during operation. The effect of an assumed initial confidence level of 50% is also indicated in Fig. 1.

14. Fig. 1 indicates two points of importance viz

a. since it is reasonable to assume that all concerned will wish to reach confidence levels of 90-95% within the first few years, values of the ratio P/T have to be kept above about 0.5, and

while it is important to establish some moderate degree of confidence before operation commences, even an initial confidence level of 50% does little to reduce the time required to reach 90-95% by routine tests.

DESIGN FOR RELIABILITY VERIFICATION

15. In the course of time it may come to be regarded as essential that the claimed reliability of safety-related systems including DHR, be demonstrated on the plant. Such a requirement would presumably define an initial confidence level and a time limit for reaching a higher level, and might or might not make an allowance for predictions made by a defined method. In either event it will be encumbant on designers to ensure that the required tests and test frequencies are practical.

16. Let us suppose for the moment that initial tests were required to demonstrate the reliability to 50% confidence level and that test frequencies were required to give a 95% confidence level within 5 years (i.e., a P/T ratio of 0.5). Table 1 shows what such a regulation would mean for various system reliabilities.

TABLE 1

Probability of failure on demand	No. of Tests Initial	Per Year
10^{-1}	7	5
5×10^{-2}	14	10
2×10^{-2}	34	25
10^{-2}	69	50

Whereas 10^{-1} gives initial tests within the normal shake-down range and a generally acceptable test frequency, practicability on both initial and routine tests is disappearing rapidly in the probability range 5×10^{-2} to 2×10^{-2}. The implication being that designers might have to tend towards greater multiplicity of systems so that less reliability per system need be claimed. Inevitably this will increase the segregation and economic problems.

TRANSFERABILITY OF TEST RESULTS

17. DHR provisions will often include several identical systems. The number of tests required can be reduced if test results can be regarded as transferable between identical systems. It would be advantageous to designers and operators, if an acceptable formula for transferability could be established. Clearly "shake-down" tests are not transferable but thereafter a case surely exists. Since 10 tests might be regarded as a reasonable upper limit for shake-down tests, could it not be agreed that results of tests beyond the first 10 on each system, can be transferred to identical systems?

18. The effect of such a ruling is demonstrated in Table 2, which also demonstrates the effect of the use of greater redundancy.

TABLE 2

1 System Required to function out of a total of	Overall Target (fpd)	System Target (fpd)	Tests Required on Each System (a)*	(b)*
3	10^{-6}	10^{-2}	300	103
6	10^{-6}	10^{-1}	30	15

*(a) assuming units are not identical or transferability of test data between identical units is not allowed,

(b) assuming units are all identical and transferability allowed.

TESTS AT PFR

19. As stated earlier, the tests on PFR, DHR and DHR-related systems are not designed to confirm predicted reliability data (with the exception of the diesel engine starts although they will make a contribution towards that. The number of initial tests (usually shake-down) conducted or intended and the intended test frequencies are shown in Table 3.

TABLE 3

Systems	Initial Tests	Routine Test per year 1/T	Target Reliability P(fpd)	$\frac{P}{T}$	Time to reach CL of 95% on tests alone
Steam Dump			10^{-2}		
Th Syphon Loops (each)	10		10^{-2}	0.06	48 years
Pony Motors (each)	10	6	10^{-2}	0.06	48 years
Diesel Engines (each)	60	50	5×10^{-2}	2.5	Nil

21. In addition to the above tests, a cautious series of progressive tests is being developed to establish the natural circulation performance of the primary sodium circuit, in coincidence with the development of a mathematical model. This series has two objectives viz (a) to demonstrate that natural circulation can take over from forced circulation a few minutes after a trip, which is confidently expected to be the case, and (b) to demonstrate that natural circulation will suffice from the moment of trip, in which case the pony motors would become redundant from the purely safety point of view.

APPENDIX

TESTS OF DECAY HEAT REMOVAL SYSTEMS ON PFR

Introduction

1. This appendix describes the tests carried out and planned by the operators on the DHR and DHR-related systems on PFR.

Plant Description

2. Decay heat can be removed from the PFR primary sodium pool either via the secondary sodium and steam circuits to the condenser (with steam dumping in emergency) or via 3 NaK filled thermal syphon loops to the atmosphere. The loops are virtually identical to each other. Each loop comprises 2 heat exchange coils located immediately above 2 of the 6 main primary/secondary heat exchangers (IHX) within the primary pool. These 2 DHR coils are connected in parallel and the NaK is then piped to a NaK/air heat exchanger located near the top of the secondary containment building. The NaK/air HE is enclosed within a duct both ends of which are open to the atmosphere outside the secondary containment building. The duct contains a damper (normally closed) and two fans (normally stopped). The damper is pneumatically operated and the fans are powered from the Guaranteed Interruptable (GI) supply.

3. It is also necessary of course, to ensure adequate heat transfer from the core to the primary pool. This is achieved by the forced circulation provided by 3 primary pumps driven by their main motors, or on their simultaneous failure (e.g. electrical supply failure) by pony motors which receive their power from the Guaranteed Non-Interruptable (GNI) supply. During normal operation the pony motors are running but the clutch between each pony motor and each pump is disengaged. These clutches close automatically when the pump speed falls to the synchronous speed.

4. The high integrity electrical supplies comprise the Guaranteed Non-Interruptable (GNI) system, powered from batteries which are normally floating, and the Guaranteed Interruptable (GI) system which is powered from 1 out of 2 diesel alternators which are not normally running. Loss of normal electrical supplies causes the duty diesel to start automatically and the appropriate circuit breaker to close onto the bus bars. A number of plant items are supplied from this GI system including the DHR fans and the GNI rectifiers.

Tests

Diesel Engines

5. A programme of 60 test starts on each of the 2 diesel engines has been conducted. During the earlier part of the programme occasional reluctance/failure of an air admittance valve (there are 2 in parallel on each engine) was observed. This only occurred when the automatic (i.e. intermittent) lubrication pump was running. The trouble was traced to a back-pressure issue and the problem was eliminated by a modification to the lubrication pump arrangements. The number of tests was raised to compensate, and test programme completed without further incident. Routine weekly tests were then established.

Thermal Syphon Loops

6. The first functional tests of the loops indicated that the NaK was circulating in the wrong direction. Tests proved that the method of filling determines the flow direction. This arises from the fact that NaK cannot be drained from the coils in the reactor tank and this will remain hotter than the NaK being added to refill the loop. Correction of the flow direction was achieved by changing the filling procedure so as to add the NaK to the downcoming pipe.

7. The intention was to perform about 10 starts on each loop during the commissioning. A combined functional/performance check on each loop is planned for the end of each schedule operating period, (i.e. about 6 per year) during normal operation. The actual number of loop starts has now reached 143 and there have been no failures to start.

8. The loops have been filled for about 18 months and there has been only one adverse event. A leak occurred in the NaK/air heat exchanger on loop B recently. The NaK was dumped and the fans stopped and damper closed to assist the termination of the fire. It has now been established that the leakage was from a "crack" on one of the 40 drawn -Ts on one of the manifolds. It is thought that this arose from a fold in the original tube, and it is expected that this will be confirmed when the section is cut-out, and examined. Preparations to do that and to replace the tube are underway.

9. The heat rejection of the loops is dependent on the core mixed mean

outlet temperature. Consequently the first performance tests cover the range up to 400°C only. At that temperature the measured heat rejection of the loops was 3.7 MW per loop, which is about 15% higher than the design figure, the increase being due to a higher air flow than expected. With the fans off the heat rejection measured was 0.9 MW per loop, which is in close agreement with expectations.

10. During reactor operation with less than 3 secondary circuits operational, some of the IHX valves would be closed. These would be opened following trips involving loss of secondary circuit cooling. Nevertheless, the performance of the loops with one and both associated IHX valves closed has been measured. With primary pumps on the closure of one IHX valve reduces the heat rejection by less than 5% and having both valves closed only doubles the reduction. Calculations indicate that a leakage flow of only a few percent would account for the high heat rejection which remains after valve closure. Similar tests with pony motor flow only have not yet been performed.

11. The loop start-up time has also been confirmed as being close to the predictions. The NaK flow reaches its full value in about 3 minutes. But there have been two separate occasions when one loop (not the same one) took approximately twice as long to establish an equilibrium value of flow and when established the flow and the heat rejection was somewhat (about 20 - 30%) lower than normal. The reasons may be associated with the parallel paths provided by the 2 coils, but the instrumentation is not optimised for the resolution of that issue. The second occasion was in December, 74 and subsequently this condition has not recurred.

Pony Motors and Clutches

12. Initially there was some tendancy for the clutches to remain engaged when the main motors were running, thus overspeeding the pony motors. This appears to have been cured by the reshaping of the teeth, as the trouble has not recurred.

13. It was then intended to carry out 10 shake-down tests on each motor and clutch by tripping the main motor, following which one clutch was to have been stripped down for inspection. Two of the pony motors successfully completed the ten tests. The third failed to engage once during the series, although after the failure it operated correctly for five further tests. This clutch was subsequently stripped down for inspection. Meanwhile, the spare clutch has been brought into service and the combined number of tests on all four units has now reached 56, of which 55 were successful. It is considered that the sole mechanical failure described here is probably characteristic for early shake-down tests and there is no evidence to suggest that it is likely to be repeated.

14. During routine operation it is intended to test each of the 3 installed units after each scheduled shut-down (i.e. about 6 tests each per annum), and the suggested interval for replacement and full servicing is 3 years.

15. The initial object of the test programme is to provide confirmation of the mathematical model and thereby gain confidence for further tests of more advanced conditions. So far three tests have been conducted:-

(i) Cold Leg Test in which the reactor was essentially shut down and the decay heat effectively zero, the thermal syphon loops being used to stimulate circulation.

(ii) Hot Leg Test with the reactor at low power to stimulate decay heat, with the thermal syphon loop set to remove no more than approximately the same amount of heat as supplied by the core.

(iii) Combined Test which is a combination of the Cold Leg and Hot Leg tests, with the reactor operating at about 1.5 MW(th) and the thermal syphon loops in operation.

16. The results from these initial tests are being analysed and compared to the behaviour predicted by the mathematical model used in the design. Initial impressions are that a cross flow pattern may be present above the core which is distorting the channel outlet thermocouple readings. Procedures are being devised to enable a true picture of channel flow under natural convection conditions to be deduced. When this has been achieved, the test programme will continue to higher powers and realistic operating conditions.

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9. Decay Heat Removal for the Liquid Metal Fast Breeder Reactor

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