HEDL-SA-2326 FP

CONF-810606--88

FFTF OPERATING EXPERIENCE WITH SODIUM NATURAL CIRCULATION

SLIDES INCLUDED

T.M. Burke
S.L. Additon
T.R. Beaver
J.C. Midgett

AMERICAN NUCLEAR SOCIETY
ANNUAL MEETING

June 7-12, 1981 Miami Beach, FL

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company, a subsidiary of
Westinghouse Electric Corporation, under the Department of
Energy Contract No. DE-AC14-76FF02170
P.O. Box 1970, Richland, Washington 99352

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T. M. Burke
Hanford Engineering Development Laboratory, Richland, Wa.

S. L. Additon
Formerly, Hanford Engineering Development Laboratory, Richland, Wa.

T. R. Beaver
Hanford Engineering Development Laboratory, Richland, Wa.

C. Midgett
Hanford Engineering Development Laboratory, Richland, Wa.

PRESENTED AT 1981 ANS ANNUAL MEETING

Held At

MIAMI, FLORIDA

June 7-11, 1981

ABSTRACT

The Fast Flux Test Facility (FFTF) has been designed for passive, back-up, safety grade decay heat removal utilizing natural circulation of the sodium coolant. This paper discusses the process by which operator preparation for this emergency operating mode has been assured, in paralled with the design verification during the FFTF startup and acceptance testing program. Over the course of the test program, additional insights were gained through the testing program, through on-going plant analyses and through general safety evaluations performed throughout the nuclear industry. These insights led to development of improved operator training material for control of decay heat removal during both forced and natural circulation as well as improvements in the related plant operating procedures.

The keystone of the operator preparation activity, however, was an extensive natural circulation test program. A series of heat transport system sodium natural circulation tests was performed at the FFTF over a period of nearly two years beginning in March of 1979. Initial testing was of one secondary loop only and included no nuclear heating. Following core loading and initial criticality in 1980, reactor scrams to natural circulation were performed at several power levels as part of the power ascent and plant acceptance testing. The test series culminated with a scram from full reactor power (400 Mw) to natural circulation in both the primary and secondary loops; the plant was subsequently cooled and maintained on natural circulation for approximately 30 hours. This final test demonstrated conclusively the capability of the reactor plant to safely dissipate decay heat in the unlikely case that all sources of electric power (for coolant pump as well as normal control systems operation) are lost.

As a result of this work on operator training and procedure preparation as well as actual operating experience, the FFTF operators are well qualified and feel confident in their ability to safely perform a plant shutdown following a complete loss of electric power.

1.0 INTRODUCTION

The FFTF (Fast Flux Test Facility) has been designed to normally remove the reactor decay heat by forced circulation in one or more of the three HTS (Heat Transport System) sodium loops (each HTS loop consists of a primary and a secondary sodium loop, separated by an intermediate heat exchanger). The forced circulation is provided by the main coolant pumps driven at low speed by pony motors. Power to the pony motors is provided by either main or backup off-site power supplies or by two independent on-site diesel generators. Even though the four power sources in combination have been determined to be highly reliable, the plant is designed to readily accommodate their coincident failure, effecting decay heat removal by natural circulation of the sodium coolant. Decay heat removal by natural circulation can be controlled over an extended time period as decay power diminishes. Normally the twelve dump heat exchanger (DHX) modules dissipate decay heat via natural draft air cooling. At high decay power levels and elevated plant temperature the air flow rate is controlled, otherwise the DHX modules are progressively isolated from the plant until reactor power decays to a value below the heat loss of a single remaining module. In the extremely unlikely event that recovery was not effected in time, the last module would freeze, initiating a second phase of decay heat removal with heat loss from the primary piping and structure to the containment atmosphere and ultimately to ambient. The last primary loop would not freeze until decay heat was sufficiently low such that the reactor vessel heat loss alone would provide adequate decay heat removal.

Plant design features which aid "long term" or sustained operation with sodium natural circulation are:

1. Progressive elevation differences between the reactor, intermediate heat exchanger (IHX) and dump heat exchanger (DHX) to provide sufficient thermal driving head, as shown in Figure 1;
2. Long above-core "chimney" to enhance thermal head development;
3. Insulation of the DHX structure plus the ability to isolate the air side to minimize uncontrolled heat loss;

1.0 INTRODUCTION CONT'D.

4. The capability to selectively valve out of service individual DHX modules to effectively balance plant heat loss with decreasing decay power;
5. Emergency powered instrumentation to monitor key parameters (e. g., sodium flows and temperatures).

Design capability for decay heat removal by natural circulation does not in itself ensure a successful outcome for all possible situations leading to this event. This assurance comes only from a combination of good plant design, proper operator training which emphasizes an understanding of the key safety functions for decay heat removal, and adequate plant operating procedures dealing with operation in the natural circulation mode. An acceptance test program designed to exercise each of these features will provide the necessary verification. Accordingly, the following sections of this paper describe the "safety function" concept used as a basis for FFTF operator training in decay heat removal, the plant operating procedure used for decay heat removal by natural circulation and finally, discussion of the natural circulation acceptance test program.

2.0 SAFETY FUNCTIONS FOR DECAY HEAT REMOVAL

The concept of "safety functions" in a specified hierachy has been recommended as a means of providing the nuclear plant operator with a systematic approach for dealing with unplanned events.[(1)] Each safety function has a purpose which serves either to assure core cooling or to minimize the potential for off-site release of radioactive material. Decay heat removal training material for the FFTF has been developed around this concept of safety functions. The safety functions were used to aid understanding and facilitate recall of existing decay heat removal operating procedures and Technical Specifications.

Nine safety functions, making up the four classes identified in Reference 1, are defined for the FFTF and listed in Table 1 and Figure 2. The first four functions as well as the last one are important to decay heat removal as discussed below. The first four functions listed in Table 1 serve to assure core cooling and are of prime importance in decay heat removal considerations. The first function, Reactivity Control, emphasizes the importance of controlling the reactor fission process and power level. By definition,decay heat removal begins after reactor shutdown. The second function, Sodium Circulation Control, includes transfer of heat from the fuel to the coolent as well as transport of that heat through the Heat Transfer System (HTS) to the dump heat exchangers for decay heat removal. As noted earlier, forced circulation for decay heat removal is normally provided by pump pony motors; however the plant is also designed to provide natural sodium circulation as an alternate means of accomplishing this function for any decay heat removal condition. The flow status of each of the six sodium loops must be determined to understand how decay heat removal is being accomplished. Possible decay heat removal impact must be assessed before actions are taken which could affect sodium circulation. The third function, Heat Dissipation Control, involves the transfer of heat from the circulating sodium to the ambient air. In the first phase of decay heat removal, this function is performed by the dump heat exchanger modules. Numerous devices are available with which to influence the cooling air flow rate; control of these devices is possible from several different stations. Further control of heat dissipation can be affected by isolating individual DHX modules. Planning for and performing DHX control adjustments is one of the major operator tasks during decay heat removal. The fourth function, Coolant Inventory Control, requires both the correct total inventory in the system as well as the proper distribution of that inventory. The relatively high priority assigned to inventory control is based on the potential impact on core cooling and the sodium circulation function if this function is not satisfied. FFTF is designed to passively assure inventory control with proper plant setup prior to an event. The FFTF Technical Specifications include plant configuration requirements to ensure that the passive inventory control system for FFTF is not inadvertantly disrupted.

The final function listed in Table 1, Maintenance of Vital Auxiliaries, assures the continuing capability to accomplish the other functions. At the FFTF only the 1 E electric power supply is designed to be always available. With this one power supply available, there exists at least one means of fulfilling all of the other functions. All other vital auxiliaries afford safety margins by providing alternate means of accomplishing the remaining functions. For example, with emergency electrical power available, sodium circulation can be driven by pony motors; auxiliary heat input (by oil fired preheaters or main sodium pump operation) provides a means to delay or eliminate the need to isolate DHX modules. The hierarchy of functions summarized in Table 1 and Figure 2 has been developed and utilized in FFTF operator training and operating procedures to guide plant status assessment and establishment of priorities, if necessary, in off normal situations. The following section discusses in somewhat more detail how this concept of Safety Functions has been incorporated into the FFTF procedure for decay heat removal under natural circulation conditions.

3.0 FFTF PROCEDURE AND OPERATOR TRAINING FOR DECAY HEAT REMOVAL BY NATURAL CIRCULATION

Figure 3 presents an overall flow diagram of plant control activities following a complete loss of electrical power. It can be seen that separate instructions for decay heat removal control are provided for two cases. The first applies if the event occurs when the plant is operating at power or elevated temperatures. The second applies if the event occurs during refueling (i.e. low temperature) operation. This differentiation is made because significant DHX module over-cooling is not possible in the second case since the DHX air side is isolated when operating at refueling conditions. Also, in the first case the operator is instructed to perform a plant cooldown quickly, if possible, to prevent possible plant damage due to loss of plant H&V systems. Block number 3 for both cases is the parallel activity of restoring plant electrical power (i.e. vital auxiliaries) which is performed by a separate procedure. Inactive loop control (Block 6) applies in either case to an HTS loop without sodium circulation (faults leading to such a condition are considered highly improbable).

Some of the key steps of the natural circulation decay heat removal control procedure are discussed in more detail below:

1. Data (loop flows and temperatures) logging is initiated shortly after event initiation. The major purpose of this task is to provide information with which the operator can evaluate each loop's performance relative to the two key Safety Functions discussed in the previous section, Sodium Circulation Control and Heat Dissipation Control. Electrical power for the required instrumentation is provided by the 1 E electrical system. In addition, information required for plant control can be obtained from self-powered thermocouples provided at the outlet of each DHX module.

3.0 FFTF PROCEDURE AND OPERATOR TRAINING FOR DECAY HEAT REMOVAL BY NATURAL CIRCULATION CONT'D.

2. Priority attention is given to verifying proper DHX module configuration. The purpose of this step is to assure proper control of the heat dissipation function and especially to identify and correct any overcooling DHX modules in order to prevent premature loss of this heat sink due to freezing. During operator training and procedure performance, emphasis is placed on maintaining balanced conditions in all three heat transport loops.

3. For the event following power or high temperature operation, step (d) indicates that a rapid cooldown will be performed if possible to minimize the potential for equipment damage caused by overheating with H&V systems inoperable. Prior to initiating the rapid cooldown the operator is required to verify that access to the DHX isilation valves in not impeded (by sodium fire smoke, radiation, etc.). If access cannot be initially verified, then plant cooldown will be at the minimum rate (DHX airsides isolated) in order to prolong the time available prior to required module isolations.

4. Remote DHX temperature control requires compressed air for controller actuation. Each module is provided with a safety grade reserve air supply for this purpose (normal plant instrument air would generally not be available following a loss of electric power). However, the reserve air quantity is generally not sufficient to perform the entire cooldown with remote DHX control. Thus at some point the plant operators must assume local manual control.

5. Loop performance relative to sodium circulation is assessed periodically. If a loop is determined to be "inactive" (no flow in

3.0 FFTF PROCEDURE AND OPERATOR TRAINING FOR DECAY HEAT REMOVAL BY NATURAL CIRCULATION CONT'D.

5. primary and/or secondary loop and thus not contributing to decay heat removal), its airside is solated to minimize heat loss. The loop sodium isolation valves will be closed prior to freezing to prevent any potential adverse impact on the remaining loops.

6. A DHX module isolation sequence (which balances on line DHX heat loss with decay power) is developed based on an appropriate decay heat curve and the ambient temperature. Actual isolations are performed when both minimum time and temperature requirements are met. The isolation sequence is intended to maintain modules on line as long as possbile in order to maximize decay heat removal path redundancy. If electrical power recovery steps are unsuccessful, the module isolation sequence would continue until only a single DHX module remained in service. Recovery of forced circulation and of auxiliary heat input would be expected prior to freezing of the last module. However, should this last module freeze, studies have shown that the decay heat level would be sufficiently low that the primary loop piping heat loss would afford and adequate heat sink.

The operator training and qualification programs at the FFTF include fairly extensive coverage of the decay heat removal concepts and procedures. However, the apparent complexity of the procedure for control of decay heat removal during natural circulation led to a desire to actually perform the procedure in the plant to verify its adequacy and identify possible improvements. The next section of this paper presents a discussion of all natural circulation tests performed at the FFTF to date, including a prototypic scram to natural circulation from full power and the subsequent cooldown using the procedure discussed above.

4.0 FFTF NATURAL CIRCULATION TESTING

The principal objectives of the FFTF natural circulation test series were to confirm adequate plant heat rejection capability by natural circulation and to collect data for verification and improvement of analytical models for predicting natural circulation. In addition, the test series also provided an excellent opportunity for the plant operators to become familiar with the plant response characteristics through actual experience and for verification of the emergency operating procedure. The test series progression was developed to minimize the potential for damage to FFTF fuel or components by incremently demonstrating plant capability. Thus the series began with a low risk subsystem test and culminated with a prototypic scram from full power to natural circulation conditions. Prior to each test, plant operators received detailed training on the purpose, expected plant response and identified contingencies. Data from the previous tests were utilized to calibrate models used to project results of the next test prior to its actual performance. Each of the FFTF tests is discussed below.

The initial FFTF natural circulation tests consisted of establishing natural circulation in one secondary loop and involved no nuclear heating. Heat input was provided by running the three primary pumps as well as the two remaining secondary pumps. This testing, first performed at 700°F sodium temperature and then repeated at 400°F, demonstrated satisfactory secondary loop natural circulation performance and a large (∿50°C) margin to sodium freezing during transition from prototypic refueling conditions[2]. This was a significant result in that establishment of natural circulation flow in a secondary loop from refueling conditions had been identified as potentially design limiting due to the relatively small transient temperature change permitted without risk of freezing.

Following initial core loading and criticality, a series of reactor scram to natural circulation tests was performed from successively higher initial reactor power levels, culminating in a test from full power, which could be used to extrapolate to the design case end of life scram to natural circulation. This progression of four tests is shown in Figure 4 (based on "Safety Model" results, e.g., high system pressure drop and decay heat). Test points three and four were selected based on the prediction that the results could be extrapolated to the end-of-life design case (point five).

The initial scram to natural circulation was performed from 5% power/ 75% flow. The test demonstrated a rapid and smooth transition to natural circulation with continuous positive flow indication provided throughout the test. The measured data agreed very well with the nominal prediction and thus provided confidence in analytical modeling, permitting testing at the next higher power level. The second test, initiated from 35% power/75% flow, included a feature to investigate potential loop interaction effects in the unlikely event of a compound failure which might cause significant asymmetric loop response during a natural circulation transient. Specifically, the pony motor in one secondary loop was left operating in order to generate a considerably higher thermal driving head in the corresponding primary loop. This loop imbalance was predicted well by the analytical models. Further, it confirmed that feasible imbalances were unlikely to disrupt loop flow.

Tests three and four were designed to allow more accurate extrapolation to the design case. Accordingly, time at power was short (hours) for test three and long (days) for test four to increase the difference between results of the two tests. The results of all the transient tests agreed well with the nominal predictions (average subassembly temperature rise predicted within 10°C) and provided confidence in the analytical results for the design case.

The three test scrams from less than full power to natural circulation were of short duration and thus tested only the initial transition and short term plant operation and operator response. The test from full power was designed to perform a prototypic long term plant cooldown under natural circulation flow conditions as well. This test thus examined all aspects of the procedure for decay heat removal control during the unexpected total loss of power event including the following:

1. Loss of normal plant instrumentation and controls (e.g., for the DHX modules) thus requiring use of emergency and eventually manual controls to effect a rapid cooldown.

2. Determination and performance of a DHX module isolation sequence to balance plant heat loss with decay heat and thus provide acceptable margin to freezing for the online modules.

3. The DHX module isolations were performed until only one module (of the normal four) remained online in each loop. At this point the secondary flow dropped below the primary flow (plant design is such that secondary natural circulation flow is normally higher than primary). At this point the thermal center of the IHX moved down from the top reducing the driving head in the primary loop.

The plant cooldown portion of the test lasted approximately 27 hours. Throughout this test both the plant and plant operators performed extremely well. Transition from normal to emergency and finally to manual control of the DHX dampers was anticipated and carried out without incident. Even during manual control, plant cooldown was easily controlled. The plant response to module isolations was essentially as predicted. No drastic change or instability in primary loop flows was observed following the module isolations.

5. SUMMARY

The series of natural circulation tests performed at the FFTF has demonstrated conclusively the ability of the plant to safely perform a transition to natural circulation from either full power or refueling conditions. Long term cooling capability has also been demonstrated by operation on natural circulation for approximately 30 hours, including use of emergency controls and isolation of three of four DHX modules in each loop. This test series, in conjunction with extensive operator training and plant procedure preparation, has not only demonstrated this capability but has also provided the plant operators with an excellent opportunity to experience plant control in this unexpected plant configuration. As a result, the plant operators are now prepared to ensure a safe plant shutdown following a complete loss of electric power or an alternate event which requires sodium natural circulation for core cooling

REFERENCES

1. "The Operators Role and Safety Fuctions," Combustion, June 1980 pp. 28-39.

2. T.R. Beaver, D. M. Turner and S. L. Additon, "Post Test Evaluation of Natural Circulation in FFTF Secondary Loops," Specialists Meeting on Decay Heat Removal and Natural Circulation in FBRs, Brookhaven National Laboratory, February 28-29, 1980.

TABLE I FFTF SAFETY FUNCTIONS

Safety Function		Purpose
F1.	Reactivity Control	Control reactor power; shutdown fission process when required.
F2.	Sodium Circulation Control	Cool fuel and transport heat to heat sink.
F3.	Heat Dissipation Control	Transfer heat from coolant to ambient.
F4.	Coolant Inventory Control	Maintain coolant inventory and distribution required for sodium circulation.
F5.	Containment Isolation	Close openings in Containment to prevent radioactive material release.
F6.	Containment Parameters Control	Maintain temperature, pressure and hydrogen concentration below levels which would jeopardize containment integrity.
F7.	Ex-Containment Release	Prevent ex-containment release of radioactive material.
F8.	Irradiated Fuel Release Control	Prevent release of radioactive material from irradiated fuel.
F9.	Maintenance of Vital Auxiliaries	Maintain operability of auxiliary equipment and systems which can be used to fulfill the above-listed functions.

HTS FEATURES TO PROMOTE "OFF-NORMAL" DECAY HEAT REMOVAL

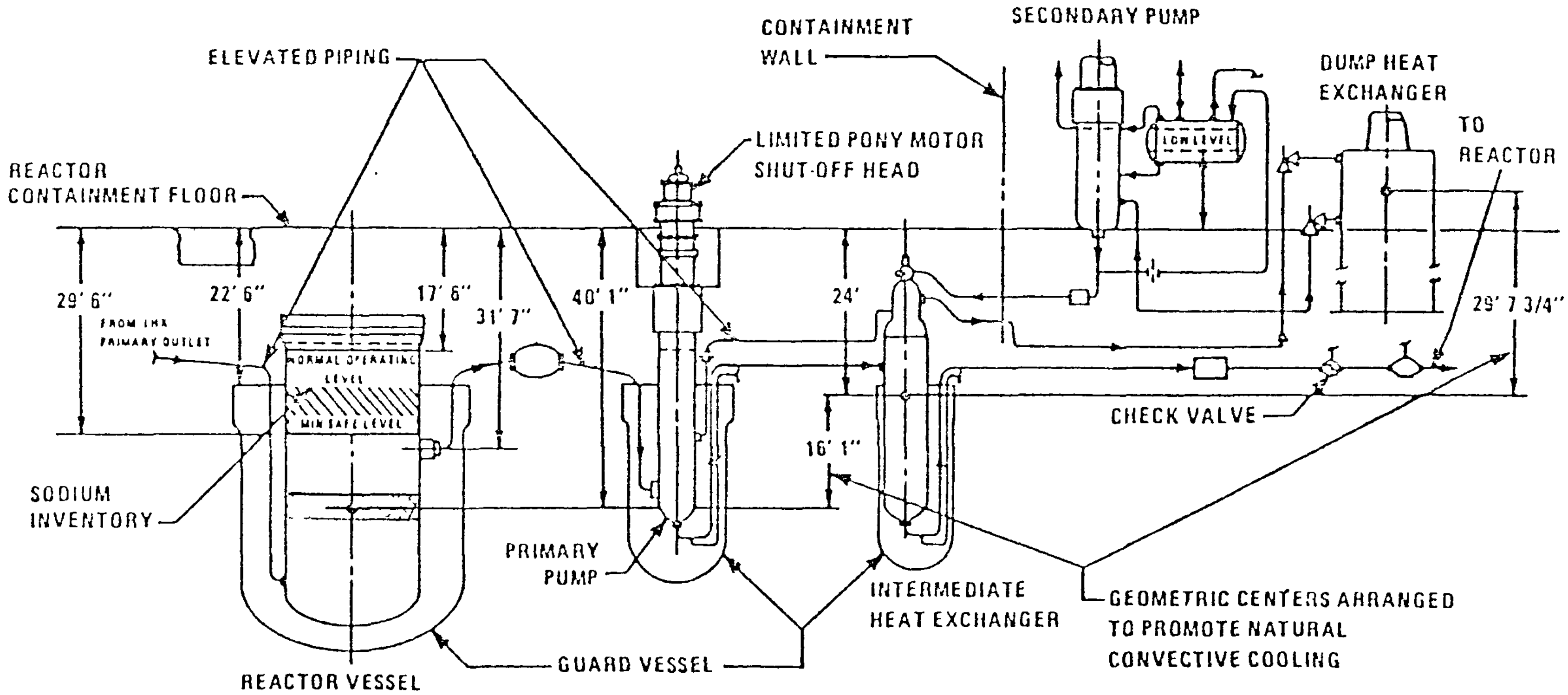
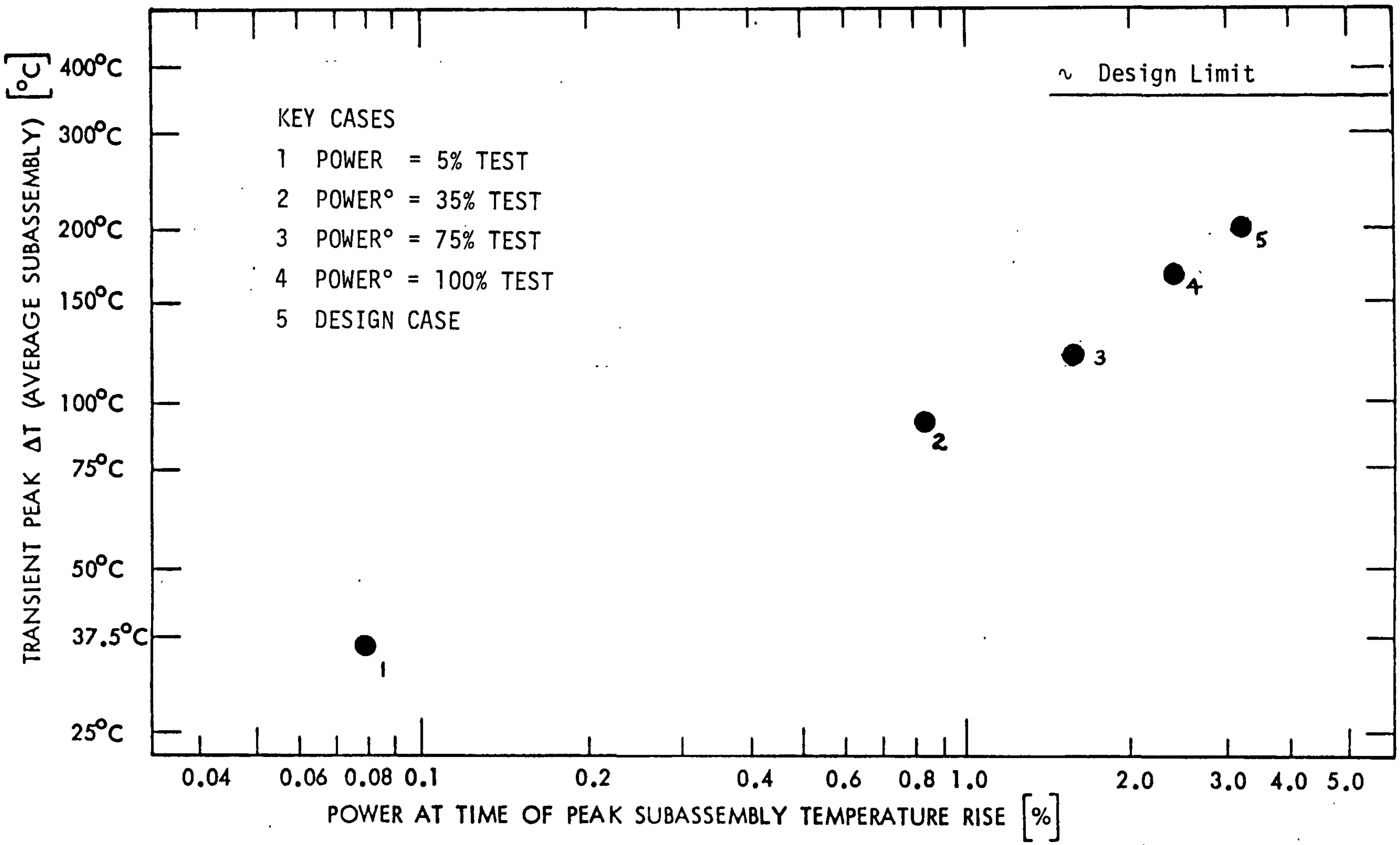


FIGURE 1

FIGURE 4

FFTF NATURAL CIRCULATION TEST POINTS



HEDL 7801-186.3

FFTF OPERATING EXPERIENCE

WITH SODIUM NATURAL CIRCULATION

BY

T. M. BURKE

HANFORD ENGINEERING DEVELOPMENT LABORATORY

FFTF OPERATING EXPERIENCE WITH SODIUM NATURAL CIRCULATION

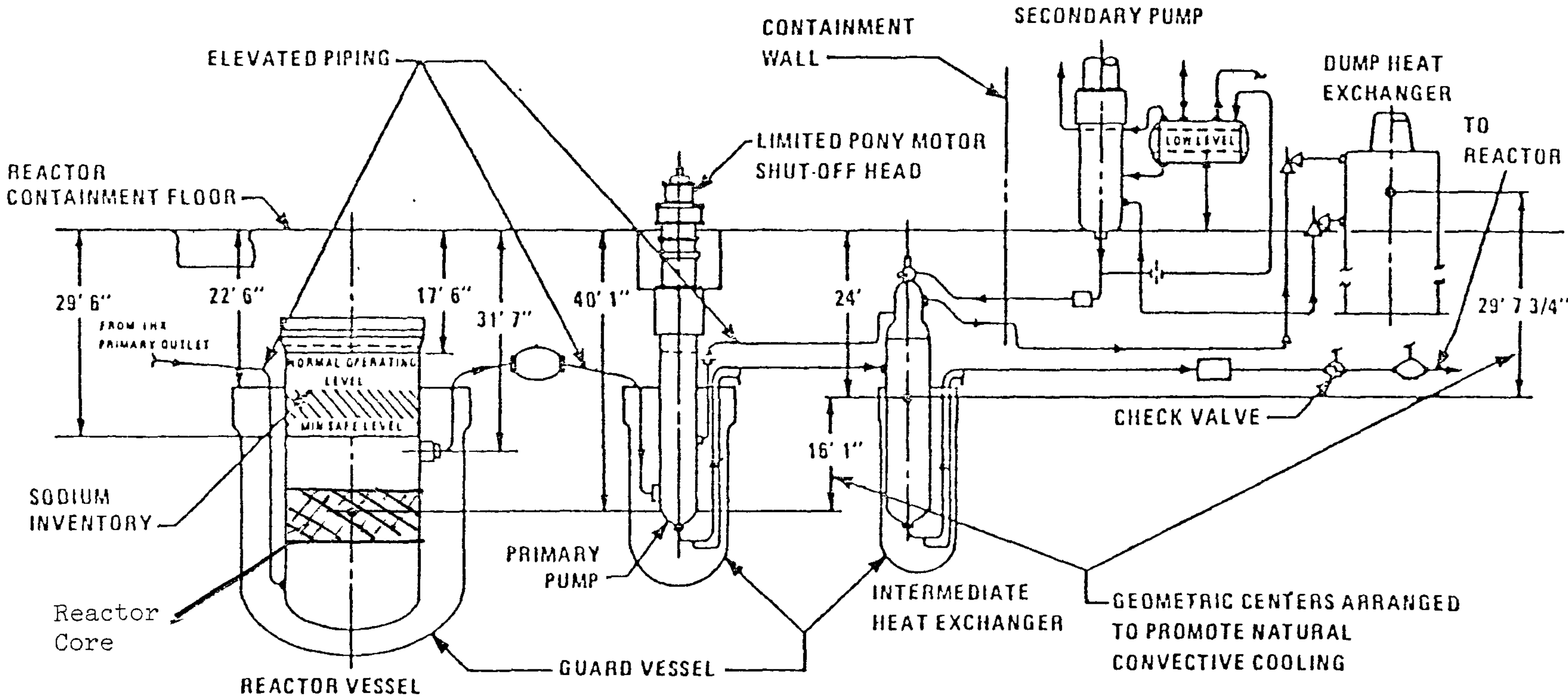
I. PLANT DESCRIPTION

II. FFTF KEY SAFETY FUNCTIONS

III. PLANT PROCEDURE FOR CONTROL OF DECAY HEAT REMOVAL DURING NATURAL CIRCULATION

IV. FFTF OPERATING EXPERIENCE

HTS FEATURES TO PROMOTE "OFF-NORMAL" DECAY HEAT REMOVAL



NATURAL CIRCULATION/DECAY HEAT REMOVAL CONTROL DESIGN FEATURES

I. PROGRESSIVE ELEVATION DIFFERENCES BETWEEN REACTOR, IHX AND DHX TO PROVIDE SUFFICIENT THERMAL DRIVING HEAD.

II. LONG ABOVE CORE "CHIMNEY" TO ENHANCE THERMAL HEAD DEVELOPMENT.

III. INSULATION OF THE DHX STRUCTURE PLUS ABILITY TO ISOLATE THE AIR SIDE TO MINIMIZE UNCONTROLLED HEAT LOSS.

IV. CAPABILITY TO SELECTIVELY VALVE INDIVIDUAL DHX MODULES OUT OF SERVICE TO BALANCE PLANT HEAT LOSS WITH DECAY POWER.

V. EMERGENCY POWERED INSTRUMENTATION TO MONITOR KEY PARAMETERS.

FFTF SAFETY FUNCTIONS

ASSURE CORE COOLING

F1. Reactivity Control (includes reactor shutdown)

F2. Sodium Circulation Control

F3. Heat Dissipation Control

F4. Coolant Inventory Control

PREVENT OFF-SITE RADIATION

MAINTAIN CONTAINMENT INTEGRITY

F5. Containment Isolation

F6. Containment Parameters Control

INDIRECT RELEASE CONTROL*

F7. Ex-Containment Release Control

- RAPS Boundary Integrity
- HTS South Confinement

F8. Irradiated Fuel Release Contr

- Integrity of Primary Syst Boundary
- Cooling and Release Barri for IDS, IEM, CLEM

F9. MAINTAIN VITAL AUXILIARIES*

- IE Electrical Power
- Emergency Electrical Power
- Fuel Oil
- Auxiliary Heat Input
- Vital Equipment Cooling
- Emergency Pneumatic Supplies

* Not all relevant sub-functions are listed for the functions in these classes.

FFTF NATURAL CIRCULATION TEST PROGRAM GOALS

I. CONFIRM ADEQUATE HEAT REJECTION CAPABILITY FOR THE TWO LIMITING LOEP EVENTS.

- FROM REFUELING WITHOUT DHX FREEZING
- FROM FULL POWER WITHOUT EXCESSIVE CORE TEMPERATURES

II. COLLECT DATA FOR VERIFICATION AND IMPROVEMENT OF ANALYTICAL MODELS.

III. CONFIRM ADEQUACY OF PLANT PROCEDURES AND OPERATOR TRAINING.

IV. ESTABLISH TEST PROGRESSION TO MINIMIZE POTENTIAL FOR DAMAGE TO FFTF FUEL OR COMPONENTS.

FFTF NATURAL CIRCULATION TEST PROGRESSION

I. SECONDARY LOOP ONLY (NO NUCLEAR HEATING).

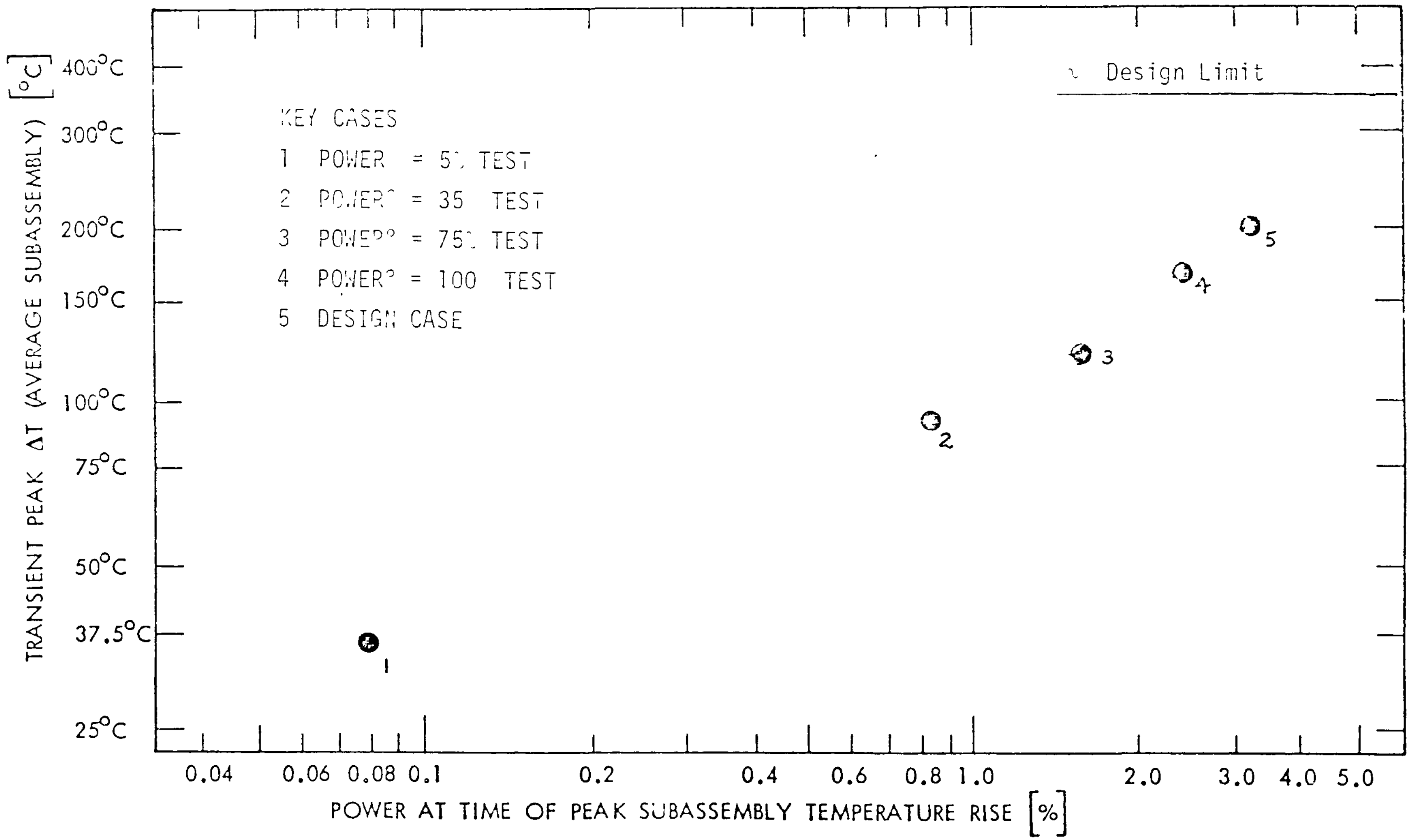
II. REACTOR SCRAM TO NATURAL CIRCULATION FROM:

- 5% POWER / 75% FLOW
- 35% POWER / 75% FLOW
- 75% POWER / 75% FLOW
- 100% POWER /100% FLOW

III. LONG TERM PLANT COOLDOWN ON NATURAL CIRCULATION.

FIGURE 4

FFTF NATURAL CIRCULATION TEST POINTS



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TRANSITION TO NATURAL CIRCULATION TEST RESULTS

I. RAPID AND SMOOTH TRANSITION WITH POSITIVE FLOW INDICATION THROUGHOUT THE TESTS.

II. LARGE MARGIN TO FREEZING (~50°C) FROM REFUELING CONDITIONS.

III. PEAK TEMPERATURES FROM REACTOR SCRAM CASES WITHIN ~10°C OF PREDICTIONS INDICATING ACCURATE MODELING AND ACCEPTABLE DESIGN CASE RESULTS.

IV. 35% SCRAM TEST RESULTS WITH UNBALANCED LOOP CONFIGURATION SHOWED NO ADVERSE EFFECTS.

RESULTS OF COOLDOWN TEST FOLLOWING SCRAM FROM 100% POWER

I. PLANT RESPONSE EXTREMELY STABLE, CONTROLLABLE AND ESSENTIALLY AS PREDICTED.

II. OPERATORS DEMONSTRATED THEIR ABILITY TO EASILY PERFORM REQUIRED CONTROL ACTIONS.

III. DHX MODULE ISOLATIONS WERE PERFORMED WITHOUT INCIDENT. NO UNANTICIPATED RESPONSE WAS OBSERVED.

SUMMARY

I. THE RECENTLY COMPLETED TEST SERIES CONCLUSIVELY DEMONSTRATES THE CAPABILITY OF THE FFTF TO BE SAFELY SHUTDOWN FOLLOWING A COMPLETE LOSS OF ELECTRIC POWER EVENT.

II. THE PLANT OPERATORS ARE WELL QUALIFIED AND PROCEDURES ADEQUATELY WRITTEN TO HANDLE THIS UNLIKELY EVENT.

III. DATA OBTAINED DURING THIS TEST PROGRAM CLEARLY DEMONSTRATES THE ADEQUACY OF THE ANALYTICAL MODELS USED TO PREDICT NATURAL CIRCULATION.