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COMPARISON OF ANALYTICAL AND EXPERIMENTAL

FLOW INDUCED CORE VIBRATIONS

(TITLE UNCLASSIFIED)

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ABSTRACT

Comparison of analytical and experimental flow induced core vibrations has been made for all applicable tests performed to date. These include the KIWI B-4A and B-4B reactors, the KIWI PIE tests and the A-11 component tests. It can be concluded that the analog and experimental results are in good agreement. Similar calculations on the NRX-A reactor design indicate that vibrations will not occur.

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1.0 INTRODUCTION

Since the KIWI B-4A hot test, considerable analytical and experimental work has been done on flow induced core vibrations. Some of the analytical work done at WANL is reported in WANL-TME-423,* WANL-TME-461, WANL-TME-447 and WANL-TME-485. Experimental work done or planned at WANL consists of the A-11 and G-3 component tests. The KIWI B-4A cold flow, KIWI PIE, and KIWI B-4B experiments have been performed at LASL. The purpose of this report is to summarize the work done to date and to compare analytical and experimental results in fulfillment of the NRX-A1 test prerequisite of WANL-TME-490 Page 2. This prerequisite reads as follows:

"Proof of stability against gross flow-excited vibrations is to be provided by an analytical model whose results are consistent with results of the following tests:

For Stage A: (NRX-A1 Non-Nuclear Test)

(a) KIWI B-4A hot and cold flow tests. KIWI B-4B cold flow test; KIWI PIE mockups of KIWI B-4A and KIWI B-4B.

(b) A-11 (flow induced vibration) component test, which will have been stable under closest possible simulation of NRX-A1 conditions, or G-3 plugged core flow tests."

Since the G-3 test has not yet been conducted, the A-11 experiment in a configuration as close as possible to the NRX-A1 is used for the prerequisite evaluation.

* See References

2.0 CONCLUSIONS

The analytical model results compare favorably with the KIWI B-4A and B-4B cold flow tests and the KIWI PIE test.

The A-11, 7 cluster test did not vibrate in the closest possible configuration to the NRX-A1, which is consistent with the analog model results. Analog results indicate that the system will not vibrate unless A-11 is assembled in configuration approximating the KIWI B-4A.

The NRX-A and G-3 experiments will not vibrate in the design configuration per the analytical model unless gross malfunctions of the lateral support seal system and core band occur.

It can be concluded that the results of all tests performed to date and the analog model results are in rather good agreement and meet the NRX-A1 test prerequisite requirements.

3.0 GENERAL DESCRIPTION OF ANALYTICAL MODEL USED FOR ANALYSIS

Before describing the analytical model a general description of a typical core will be presented. The basic structure in the core is the fuel element. This is a hexagonal rod of fueled graphite approximately 52 inches long and 0.75 inches across flats with axial coolant holes through it. Six fuel elements are arranged around a center hexagonal unfueled graphite rod to form a cluster. The seven elements are held together at the top (cold) end by a metallic plate and at the bottom (hot) end by a graphite support block. A tie rod through the central element is attached to an upper support plate and compresses the cluster against a spring. The clusters are arranged to form a nearly circular cross section. To round out the core irregular clusters, filler strips and/or slats are used. Figure 1 is a cross sectional view of the NRX-A1 core.

The lateral support configuration depends upon the design (KWII B-4A, NRX-A1, etc.). The lateral support is used to hold the core together and allow for thermal expansion.

The analytical model is designed for use with an analog computer and represents two cluster assemblies in the core leakage flow stream. The inner beam represents a normal fuel cluster such as is found in the center portion of the core. The outer beam represents a peripheral fuel cluster that has added mass and stiffness due to filler strips and pyro tiles. In the case of the NRX-A1 it was necessary to assume that the seal rings stay in contact with the outer beam because of computer equipment limitations. Figure 2 shows the generalized two beam model. Each cluster is represented by a four axial section approximation to a continuous beam and the beams require end fixity conditions.

Flow balance equations are written about twelve inter-cluster volumes.

Both axial and radial flows into and out of these volumes are considered. In general, the flow resistances are functions of the cluster displacements.

The lateral support springs are assumed to act at each axial section of the outer cluster. Simulation of collision between clusters and between clusters and the inner reflector is achieved in the model. The pressures external to the inner reflector, at the core inlet and at the core exit are determined by the main flow and are input values to the calculation. The leakage volume pressures and cluster displacements are determined by the analog computer as a function of time.

A detailed discussion of this model is presented in WANL-TME-423.

4.0 COMPARISON OF ANALYTICAL RESULTS WITH EXPERIMENTS

4.1 KIWI B-4A

4.1.1 KIWI B-4A Hot and Cold Flow and KIWI B-4A PIE Tests

Certain vibration, neutronic, acoustic, control rod position, and control rod torque channels indicated relatively high level 20-33 cps oscillations during the KIWI B-4A hot run (Ref. 5). This vibration damaged the core by breaking the fuel elements. Some of the conclusions reached are as follows:

- (1) The reactivity perturbations were caused by physical vibrations of the core.
- (2) The amplitude of the vibrations was sufficiently large during part of the run to cause collisions with the reflector.
- (3) The KIWI B-4A core was spring-loaded to compress the core toward the center line. There was a void approximately 0.2 inches wide between the core and reflector with a cold compacted core. This space was open to core exit pressure. There was a second void between elements in the core. With flow and a compacted core the internal core pressures were higher than the pressures in the reflector core space. This pressure difference caused the core to expand out toward the reflector and at appropriate flow rates the resulting pressure forces and beam dynamics of the clusters resulted in destructive vibration.

After the KIWI B-4A hot test it was decided to run a cold flow test to obtain a better understanding of the vibration problem. During selected portions of the KIWI B-4A Cold Flow Test, high speed motion picture photographs were taken of a portion of the core exit plane to record motions of the core support blocks. Three types of gases were used and steps or ramps were used in the mass flow rate. Some semi-quantitative impressions obtained from this test are:

- (1) The core may have vibrated as clusters, remaining more or less in place until collisions occurred. There was fuel element bending.
- (2) Frequency was roughly proportional to the square root of flow rate, covering the range 18 to 35 cps.
- (3) The threshold of vibration for hydrogen and helium is much lower than nitrogen.

Spectral analysis on some of this data was done at both LASL and WANL. The analysis done at WANL is reported in WANL-TME-447.

The KIWI PIE experiment consisted of a one-sixth pie shaped slice of a KIWI B-4 core full scale. The core was mocked up in exact detail out to the outside diameter of the graphite reflector cylinder. The fuel element coolant holes were plugged. Four inch round ports to allow visual observation of the core vibrations were provided for in the pressure vessel. The design was such as to allow entire alternate lateral support designs.

The same general conclusions were reached from the KIWI PIE B-4A simulation as from the KIWI B-4A cold flow.

4.1.2 KIWI B-4A Analytical Results

Since the analytical model simulates the two outer most clusters in the core the analog results for a KIWI test of KIWI PIE test would be the same with the same lateral support system. The analog flow equations are valid only for a quasi-steady state operation about an operating point.

The KIWI B-4A displacement characteristics at four ambient hydrogen flow rates are shown in Figure 3. The results shown in this figure were made using a clamped inlet condition (simulating the tie rod and seal restraint on the clusters at the inlet end) and a free exit end condition. At 8 lb/sec and 5.4 lb/sec gaseous hydrogen flow rates, two modes of vibration were found. The first part of the traces shown a low amplitude vibration. The system was externally excited and a second mode appeared which was self-sustaining. The frequency from the analog at 8 lb/sec was 35 cps as compared to 28 cps for test results.

An empirical relation, obtained from test results, indicated that the frequency of the KIWI B-4A vibration was approximately proportional to the square root of the flow rate. The data at 8 lb/sec and 5.4 lb/sec agree quite well with this relation ($35/30 = 1.17$, $8/5.4 = 1.21$).

At 2.7 lb/sec gaseous hydrogen flow rate on Figure 3, the KIWI B-4A core seems to be at a threshold of vibration. The system does not sustain any vibration but an external excitation damps out quite slowly. At 0.27 lb/sec flow rate there is no steady state brooming and after external excitation the core returns to a steady state somewhat faster than the 2.7 lb/sec flow rate. The analytical model, therefore, predicts sustained

vibration at a gaseous hydrogen flow rate between 2.7 and 5.4 lb/sec. The KIWI B-4A cold flow experiment demonstrated sustained vibration at 4.5 lb/sec.

The traces on Figure 4, when compared with those on Figure 3, indicate that the tendency to vibrate is significantly less when gaseous nitrogen is used instead of gaseous hydrogen. The nitrogen flow rates on Figure 4 were scaled to give the same pressure distribution on the analytical model core boundaries as used for hydrogen in Figure 3. Similarities in response, when compared with gaseous hydrogen, are: no brooming at lowest flow rate, two modes or states for the higher flow rates, and similar magnitudes of brooming for the comparable flow rates.

The difference between gaseous hydrogen and nitrogen is in the gas damping forces with nitrogen providing much larger damping. This analytical result is in agreement with observed KIWI B-4A results where higher flow rates on nitrogen were required to sustain vibration of the clusters.

Figure 5 presents the analog results for the KIWI B-4A with free inlet beam end conditions and a free exit end condition at 8 lb/sec gaseous hydrogen flow rate. At the far left of this figure is the normal B-4A which again shows the two modes of vibration, then the NRX lateral support springs were added. Here the NRX springs stop the vibration and after excitation vibration could not be excited. Further to the right the NRX springs are removed and the B-4A conditions previously observed return. The results of this run at 8 lb/sec show that the inlet beam end condition (fixed or free) is not a significant factor in the vibration of the KIWI B-4A.

It was necessary to reduce the analog equipment which the model used from a three console problem to a two console problem. To do this the flow equations were reprogrammed, however, there were no additional assumptions or approximations introduced. Figure 6 shows the KIWI B-4A displacements at 8 lb/sec flow rate for the two console problem, this figure compares quite well with Figure 5 except the frequency dropped from 35 cps to 32 cps, which is closer to experimental results (28 cps). This change in frequency is felt to be within the expected range of reproducibility due to change of equipment characteristics and considerations such as potentiometer drift.

4.2 KIWI B-4B

4.2.1 KIWI B-4B Cold Flow and KIWI B-4B PIE Tests

The KIWI B-4B configuration is similar to the KIWI B-4A except the B-4B had a single hot end seal instead of a cold end seal and much stiffer springs. LASL ran a cold flow experiment on this configuration August 21, 1963, with several flow rate steps and ramps. The fluids used were gaseous nitrogen, gaseous hydrogen and liquid hydrogen. The damaging vibration that was present in the B-4A test was not present in the B-4B test, and there was no indication of core "brooming" or vibration by instrumentation or movie camera.

The KIWI PIE with KIWI B-4A springs was modified to mockup the KIWI B-4B by inserting a bladder for a bottom seal. Flow experiments on this mockup showed only a steady compression of the core with increasing flow rate. However on changes in the pressure level, slight oscillations were observed at the inlet end of the core and damped rapidly as equilibrium flow conditions were reached.

4.2.2 KIWI B-4B Analytical Results

The right portion of Figure 5 represents an analytical simulation of the KIWI B-4B tests. Starting with a vibrating B-4A configuration the nozzle end seal was added in stages by varying the leakage. Vibration was reduced with each additional increment of effectiveness of the seal but did not stop completely until the seal was perfect. The non-vibrating state could not be excited into a vibratory mode. Additional analog runs simulating the KIWI B-4B design which has stiffer lateral support springs than the KIWI B-4A indicated that this reactor would not vibrate with normal B-4B spring or seal conditions.

4.3 A-11 Component Tests

4.3.1 NRX-A Configuration Test

The A-11 test is a seven cluster core with filler strips and pyro tiles rounding it out. The lateral support system design tested to date is that of the NRX-A1. The coolant channels in the non-fueled graphite elements are orificed with 0.060" orifices. The results of flow tests up to nearly 100% of design pressure drop across the core have indicated no flow instabilities, with the simulated NRX-A1 configuration.

4.3.2 NRX-A Analytical Results

In order to study the A-11 configuration the model was changed to a one beam approximation because the A-11 has only seven clusters (one central surrounded by six others). On the A-11 a hinged inlet beam condition was used. With the NRX-A lateral support system as designed and the one beam analytical model no vibration modes were found.

It had been confirmed earlier that no vibration existed if the model was assumed to be a two beam configuration or to have clamped inlet end fixity (Ref. 3).

4.3.3 KIWI B-4A Configuration Test

An attempt to convert the A-11 to the KIWI B-4A configuration was made by milling out the seals in the lateral support to make them ineffective and by providing weaker springs. This configuration did not vibrate and after disassembly it was found that the 17th seal was not milled out properly and was effective. The configuration as tested more nearly duplicated the KIWI B-4B with hot end seal and is discussed in Section 4.2.1.

4.3.4 KIWI B-4A Analytical Results

Figure 7 shows the displacements for a one beam model with the KIWI B-4A lateral support system and hinged inlet beam end condition and free exit beam end condition. The one beam approximation displacement traces are more regular than the two beam approximation but the frequency is the same. Thus, it is assumed that an A-11 configuration duplicating the KIWI B-4A will vibrate. Future tests are planned to verify this.

In this figure the left portion is with NRX lateral support pin leakage and the right portion is with KIWI B-4A pin leakage. The KIWI B-4A pin leakage is approximately 1.6 times as much as the NRX configuration and shows no effect on the stability.

5.0 EXPECTED NRX-A PERFORMANCE

5.1 G-3 Component Test and NRX-A

The G-3 test unit will consist of a complete core and NRX-A1 lateral support system enclosed in a pressure vessel. The coolant channels in the core and graphite reflector will be plugged. Tubes into each seal chamber which are externally fed or exhausted allow varying the pressure distribution on the core exterior. Leakage flows and vibration measurements will be made. This test will determine the adequacy of the lateral support system in inhibiting flow induced vibrations as well as the leakage flows and pressure drops through the system. The initial test series will determine the range of stable core operation with the as designed seal passages and the effects of the independent design variables, such as core external axial pressure distribution and lateral support spring forces on the range of stability.

The NRX-A1 cold flow test series have been selected to approximate the conditions which occur in an actual reactor run during purging, inerting, shutdown, startup and cooldown operations. One of the major objectives of the NRX-A1 series is to determine the effects of the planned test conditions on the dynamic stability and structural integrity of the assembly and its components.

5.2 G-3 and NRX-A Analytical Results

The analytical model of the NRX-A applies to both the NRX-A and G-3, because the analysis considers only leakage flows and boundary pressures are input to the calculation.

One major result of the survey of the NRX is that the reference model representing clusters as clamped at the cold end and free at the hot end (design hydraulic resistances and spring rates) does not vibrate for any flow condition studied and has just one state, which is completely bundled. The clusters are fully bundled and return to this state rapidly after any artificial excitation that was introduced into the analytical model.⁽³⁾

Studying different end conditions for the normal core it was found that generally two states exist when the inlet end is not clamped (banded). The fully bundled state exists for all conditions but can be readily excited to an almost fully broomed condition by a variety of artificial excitations in the analytical model. Even though brooming of the core could occur with excitation, no vibration was found for the normal core.⁽³⁾ The partially broomed state is probably undesirable since the cluster would then respond to a flow disturbance.

With a clamped inlet end (banded) and core abnormalities of reduced effectiveness of lateral support seals and springs no case was found in which the core vibrated. Certain of the abnormal conditions did result in partial brooming but not in multiple states.

With inlet end conditions other than clamped, several cases were found where the clusters would vibrate.⁽³⁾ Generally, the vibration would be associated with the broomed state and would not occur if the core remained in the bundled state. For all vibratory cases, the vibration stopped when the inlet end was clamped. This is in contrast with the KIWI B-4A results where vibrations occurred with either clamped or free inlet end conditions.

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FIGURE 1

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FIGURE 2

GENERALIZED CORE LEAKAGE AND VIBRATION MODEL

FIGURE 3

KIWI-B4A CLUSTER VIBRATIONS AT DIFFERENT GH₂ FLOW RATES

FIGURE 4

KIWI-B4A CLUSTER VIBRATIONS AT DIFFERENT GN₂ FLOW RATES

FIGURE 5

KIWI-B4A CLUSTER VIBRATIONS WITH DIFFERENT END CONSTRAINTS

FIGURE 6 - KIWI B-4A CLUSTER VIBRATIONS 8 LB/SEC GH_2
 (TWO CONSOLE)

FIGURE 7

KIWI B-4A CLUSTER VIBRATIONS ONE BEAM APPROXIMATION