THE EXPERIMENTAL LOOP PROGRAM

G.J.Field
Manager
Fuel Channel Department
AECL CANDU
Mississauga, Ontario

INTRODUCTION

As part of the N12 investigation the fuel channel experimental loop program was set up in June 1991 to address the vibration and fretting characteristics of fuel under closely simulated reactor operating conditions in an attempt to understand and duplicate the fuel failure mechanisms which were discovered in Darlington Unit 2.

The program initially utilized three full scale fuel channels operating at or close to reactor operating conditions of temperature, flow and pressure in addition to the existing flow visualization test rig in AECL SPEL. In October 1991 the fuel channels at GE (Canada) were included in the program to undertake fuelling machine transfer function experiments and subsequently involved a series of endurance tests. Flow and pressure pulsing equipment was designed to create flow variations in the channels, and pressure pulses over a complete range of frequencies up to 300 Hz. A mechanical vibrator was utilised at OHRD to excite a fuel channel and the fuel string. Monitoring of the channels covered a range of parameters such as pressure pulse amplitude at various locations in the channel, vibration of fuel elements and channel components and strain or deflection of the outlet bundle downstream end plate. In addition, the fuel was dimensionally measured before and after test to assess the degree of cracking, inter-element spacer fretting, end plate/end plate fretting and bearing pad fretting.

The four loops were either refurbished or constructed at the OHRD Laboratories, AECL SPEL at Sheridan Park, STERN Laboratories in Hamilton and facilities of GE (Canada) at Peterborough. The OHRD and SPEL loops utilized existing Bruce channels, the loop at STERN was fitted with a new Darlington channel representing D2K12, (a D type channel) while the channels used at GE(Canada) were Darlington channels constructed in 1983 for fuelling machine commissioning.

Many of the objectives of the original test program were achieved by September 1991 and revised tests were started to assess the hypothesis that pressure pulses, caused by the 150 Hz vane passing frequency of the PHT pump, were responsible for all the known damage. The continuing investigation and particularly the measurements of pressure pulsing and end fitting axial vibration taken during reactor testing and assessment of the various failure scenarios led to a wide range of tests.

Figure 1 shows how the experimental loop program fitted into the overall N12 investigation. Results of the experiments were reported on a weekly basis to the N12 Investigating Committee.

Flow Visualization

A series of tests were undertaken during the early part of the investigation to show how damaged fuel in steady flow conditions up to 40 kg/s behaved. Whilst a significant amount of understanding of fuel performance was gained the results did not show any of the failure modes seen in the reactor. In fact under almost all test conditions the fuel remained very stable.

Flow visualization studies of the inlet end of the fuel channel were conducted to improve the understanding of flow instabilities in the inlet end fitting/Grayloc geometry. It was suspected that these contributed to the 'rocking' and hence fretting of the inlet fuel bundles. This work did show a flow instability in the annulus between the liner and the inlet end fitting body which appeared to be a function of the flow rate and created by swirl flow in the entrance region from the Grayloc. The frequency of oscillation, in general, increased linearly with flow to approximately 16 Hz at 32 kg/s flow rate. Some comparison tests were done in the ETR-7 loop under hot pressurised conditions and similar flow oscillations in the annulus were measured. Tests with alternative shield plug designs indicated that turbulence was more directly related to shield plug design.

Recent test results have shown that the position of the bundle with respect to the spacer sleeve has a significant effect on the degree of bundle 'rocking', figure 2 . This shows that the type D channels in the centre of the Darlington core are the most stable from the point of view of 'rocking' of the bundle caused by the inlet geometry.

Fuel Response to Steady State Flows

Tests with steady state turbulent flow rates up to 40 kg/s were conducted at SPEL and STERN to measure both the downstream end plate deflection and the upstream bundle axial movement for different fuel strings. Inlet bundle movement was shown to be more than expected. Figure 3 shows axial movement of the upstream bundle of up to 3 mm when increasing the flow from 0 to 30 kg/s.

The outlet bundle end plate deflection, due to hydraulic loading, was shown to be of the order of 0.5 to 1.00 mm depending on the fuel string, figure 4. These values were expected based on load shedding calculations done early in the investigation. Based on measurements of the variation in element lengths of the two manufacturers, GE (Canada) and Zircatec, the different fuel types should behave differently under similar flow conditions because of the different load shedding behaviour.

Several tests were conducted with simple axial mechanical loading to determine the mechanical spring constant of the fuel string. The intent was to provide information input to the fuel string analytical modelling. The axial spring constant of a GE fuel string was found to be about 3mm/10,000N.

Fuel Response to Pressure Pulsations

The effects of pressure pulsations on both the inlet and the outlet fuel bundles was investigated at STERN Laboratories and SPEL.

Initial results from STERN indicated that the downstream end plate of the outlet bundle responded axially to a wide range of pulsing frequencies up to 300 Hz with peaks in the displacement amplitude at many specific frequencies, figure 5. Axial amplitudes of vibration were much higher than anticipated and values up to ± 0.2 mm were measured. In general, the outlet bundle downstream endplate responded fairly easily to pressure pulsing up to approximately 140 Hz. Above this the endplate required higher pulses to attain the same deflection suggesting a loop acoustic resonance or a fuel string mechanical resonance, figure 5.

Tests in which both inlet and outlet bundle movements were monitored, using UT probes, indicated complex relationships between the two bundles. In some cases they moved in phase in others the movement was independent.

Fuel Response to Flow Variations

Changes in flow creates variations in the drag load on the fuel string and subsequently changes in the end plate stress. A calculation of the flow changes needed to meet the fatigue stress amplitude threshold indicated that ± 2 kg/s would be sufficient. A test at SPEL was carried out at approximately this flow rate variation at 1.5 Hz and a mean flow of 28 kg/s at 70 °C. The test was continued for 2.3 million cycles with no failure of the end plate and only light fretting on the inlet bundle bearing pads. Based on the fatigue curve it is possible that continued cycling, to 5 to 6 x 10^6 cycles, may have caused end plate cracking. This frequency, however, is too low to cause the high cycle/low amplitude failures seen in Darlington in the expected time frame.

Following analysis of the flow signal variations in the reactor a series of tests was conducted, at SPEL and STERN, with flow variations in the frequency range up to 40 Hz corresponding to flow variations in the range 0.5 to 1.7 kg/s. Some of these included a modulation of the basic flow as suggested by the reactor measurements. Although subsequent analysis has indicated that the reactor channel flow measurements are significantly influenced by instrument line effects, these tests provided good characterization of the inlet fuel bundle response to transient flow variations. Major results of these tests indicated a clear preference for the inlet bundle to undergo 'rocking' at a flow variation frequency of 16 Hz. The degree of rocking was relatively independent of the flow amplitude. Lateral amplitudes of motion, at the inlet bundle mid plane of up to ± 0.2 mm were measured, as compared to an expected maximum of 20 micrometres. At approximately 35 Hz, element lateral amplitudes of motion were of the order of +/- 0.5 mm.

The modulating flow tests, conducted at STERN, consisted of pulsing flow variations in the 5 to 15 Hz range whilst varying the flow rate at frequencies less than 1 Hz. In addition, random sudden drops in the flow rate of some channels were simulated.

As with the results from SPEL the inlet bundle was seen to respond significantly at a flow variation frequency of 16 Hz and was relatively independent of the flow amplitude. The modulation of the flow variations had little effect on bundle performance. Tests in which random, sudden flow decreases were created caused the inlet bundle to 'rock' momentarily at 16 Hz.

Similar testing utilising a flow straightening inlet shield plug indicated that the shield plug was transparent to such imposed flow variations in the bulk flow. The flow straightener shield plug did however significantly reduced inlet bundle rocking due to 'normal' inlet shield plug turbulence from the standard MkIIIA shield plug.

Endurance Testing

Based on calculations and fatigue testing undertaken with small samples, the fatigue deflection limit of the endplates was approximately ± 0.15mm for simple bending. Endurance testing under cold, pressurised operating conditions, whilst pulsing with a pressure pulse amplitudes at high frequency (150 Hz nominal) to maintain an end plate deflection of approximately 0.15 mm and hence to crack end plates, was initiated. A second endurance test under similar conditions was carried out to verify the previous test result.

The first test bundle was intended to maintain a constant deflection of the downstream end plate and to achieve this the frequency of the pressure pulsing had to be adjusted between 134 and 168 Hz. The objective of the test was achieved and the end plate cracked after approximately 10 million cycles. The fracture surfaces were examined and found to be a result of high cycle, low amplitude fatigue similar to those seen in the reactor but having a fretted fracture surface. Continuation of the test demonstrated that the failures propagated along the fuel string. A second test, to verify the conditions required to cause cracking, was undertaken at a constant 136 Hz pressure pulse frequency and cracking occurred after approximately 6 million cycles. Continuation of the test demonstrated that the cracking was, again, progressive with further cracks developing not only in the outlet bundle but also in bundles further down stream. The inlet bundle was carefully monitored for bearing pad fretting. The fretting rate was seen to be higher than expected but due to difficulties in measuring the bearing pad height a quantitative estimate of the fretting was not possible. These tests reproduced the essential damage features found in Darlington unit 2 - namely end plate cracking, high spacer pad fretting in bundles 1 and 2 between intermediate and inner rings, fretting between the end plates and high fretting on the inlet bundle.

Testing at GE in which the conditions were variable, covering temperatures from 60 °C to 295°C with the frequency held at 150 Hz, also resulted in cracked end plates. When the fracture surfaces were examined they were seen to be very similar in surface texture to those seen in the reactor. This result suggested that the in-reactor failures occurred under hot operating conditions. A test at 150 Hz with a reduced pressure pulse amplitude of about 25-35 Kpa and 'domed' bundles produced incipient cracks at elements 22, 26 and 30, consistent also with the cracking patterns seen in the reactor.

Testing at GE concentrated on developing a pulse amplitude threshold for end plate cracking. This threshold for GE fuel was found to be in the range 25-40 Kpa (zero to peak) pulse amplitude at the inlet bundle. Similar testing of Zircatec fuel resulted in a value of about 65 Kpa (zero to peak) pulse amplitude.

A test at 150 Hz, and 285 °C, and a pressure pulse amplitudeof 65 Kpa (zero to peak) at the fuel string inlet - created end plate cracks in bundles 1, 2, 6, 8 and 12 after 21 hrs of operation. Investigation of these cracks indicated that the crack in bundle 12 was a fresh ductile crack not caused by the test. Those in 1,2,6 and 8 were shown to be due to fatigue failure. Cracks in bundles 8 and 9 have been seen in three Darlington channels. Recently the D2 K12 #12 bundle was inspected and also found to be cracked. This test suggests that severe fuel damage in-reactor was caused by high pressure pulse amplitudes.

In order to create a significant change in the channel response, at GE, a test was conducted without an outlet shield plug. The results showed significant differences in the end plate cracking to that of a test run with the shield plug. In particular cracks were easily produced in bundles 1, 2 and 8. It is possible that the removal of the shield plug affected the mechanical response of the end fitting, the acoustic response of the channel and hence the fuel string.

An outlet fuel supporting shield plug was tested at STERN, under conditions known to cause endplate cracking. The test ran for approximately 200 hrs which was about 20 times longer than necessary to crack end plates under similar conditions with a regular shield plug. No cracking was observed. This was expected based on the reduction in high mean endplate stress. Measurement of the inlet bundle axial movement suggested that the fuel supporting shield plug did not, however, prevent axial movement and hence fretting of the inlet bundle bearing pads or the pressure tube.

Two tests of approximately 150 hrs under steady state flow were undertaken at SPEL at 265 °C and 30 kg/s flow rate with light water, in order to provide a baseline fretting rate. In both cases the inlet bundle exhibited fretting on the inlet fuel bundle bearing pads which was unexpected. This fretting was seen as a step in the bearing pad approximately 130 micrometres deep. It is, however, somewhat typical of fretting seen at Bruce 'B' and in many channels in Darlington although the duration of the test was low compared to the residence time of fuel in the reactors. It is surmised that the fretting rate is high to begin with and decreases with time. Further examination of the bearing pad fretting over the complete bundle indicated that no significant fretting existed other than on the bearing pads resting on the spacer sleeve. This fretting was considered to be due to 'rocking' of the bundle caused by flow variations/turbulence created by the geometry of the inlet Grayloc and the MkIIIA shield plug.

A review of the examination of the fracture surfaces from the reactor and the test loops concluded that the hot testing created fracture surface features closer to those seen in the reactor than did cold testing.

End Fitting Axial Motions

A series of tests was undertaken to assess if monitoring of the end fitting axial motion could provide information on the fuel string behaviour or an indication of the pressure pulse amplitude in the channel and a possible monitoring parameter for fuel behaviour in the channel. Similar tests were conducted at the three loops, SPEL, STERN and GE with conditions at the various loops up to 305 °C and 210 Hz pulsing frequency.

The results were variable, being apparently consistent at GE, indicating the method would provide a good monitoring basis, to variable at STERN and SPEL, particularly at high pressure pulse amplitudes at the inlet bundle position. The results from SPEL conducted at 210 Hz with a Zircatec fuel string, showed more consistency than at 150 Hz. In general the SPEL testing indicated few string resonances between 170 Hz and 220 Hz. The data from the three loops were correlated to determine the basis on which the end fitting axial motion could be used to monitor the reactor for conditions that could be associated with fuel damage, figure 6. This included a set of data generated at GE with no fuel in the channel. The conclusions from this comparison, in general, show that endfitting axial motion was positively correlated with the magnitude of pressure pulsation at the inlet bundle and appeared to be similar for both GE and Zircatec fuel.

Feeder/Fuel Channel Acoustics

Measurements of the pressure pulse amplitude along an inlet feeder, fuel channel and outlet feeder was accomplished at STERN following installation of extra pressure transducers in the feeder pipes. Three typical results are shown in figure 7 for 30, 150 and 210 Hz. The overall results indicated that there can be standing and travelling waves in the feeder/fuel channel combination. There can be amplification in the feeder at 150 Hz with two peaks between the inlet to the feeder and the Grayloc. The highest peak occurred approximately 2 metres upstream of the Grayloc, the amplification being a factor of two compared to the pressure pulse at the inlet to the feeder. However between the inlet to the feeder and the Grayloc there was slight amplification at low pressure pulse amplitudes and attenuation at all higher pulse amplitudes. Through the channel, from Grayloc to the latch bundle the pressure pulse amplitude generally attenuated except at the bundle position 4 where the pulse amplitude was always higher than at position 7 but still lower than at the Grayloc. Apart from the 30 Hz result it appeared that a pressure node always developed just outboard of the shield plug in the inlet end fitting.

Measurements of the pressure pulse amplitudes along the loop were not possible at GE or the SPEL loop because of the lack of pressure transducers. The experiments to date were not set up specifically to run in resonating conditions. However, resonances obviously occur in the loops as testing at 150 Hz and 265 °C in the GE loop creates a pulse amplitude under all bypass valve conditions which is very low. A significantly higher pulse amplitude is possible at either 150 Hz and 295 °C or 168 Hz and 265 °C suggesting a resonance of the loop or pulser system.

In SPEL, the loop showed several resonances and in particular a pulse absorption at about 10 Hz. These results indicated that the behaviour of the loops and presumably the channels in the reactors is acoustically very complex, a fact which could, in part, account for the variable results between the loops.

Fuel String Response to Mechanical Vibration

The effect of mechanical vibration of end fittings on the fuel and pressure tube has not previously been quantified and such testing was undertaken at OHRD-NPCTF. Several test runs were made with a mechanical vibrator attached to the inlet end of the fuel channel and used to vibrate the end fitting in a vertical direction. The results suggested that vertical accelerations of the end fitting at 150 Hz were unlikely to cause the fuel to vibrate axially but at specific frequencies could cause the fuel to impact the channel.

Axial vibration of the downstream endfitting indicated that about a 600 N alternating load is needed to cause the end fitting to vibrate at a velocity of 4 mm/sec, a value measured on the reactor. Calculations of the axial forcing function, due to pressure pulses in the feeder, suggest that this alternating load is unlikely to be achieved on reactor.

Further work at OHRD consisting of vibrating the inlet bundle directly and monitoring fuel string response using accelerometers, demonstrated a 'breakaway' behaviour, of the inlet bundle motion when subjected to a 150 Hz axial load forcing function, figure 8. Applying an additional varying load at low frequency (10 Hz) was shown to take the fuel string into and out of the 'breakaway' part of the curve. Subsequent testing covering low frequencies between 6 and 15 Hz exhibited similar behaviour. A brief test at 210 Hz also gave similar behaviour. During the testing the knee at which 'breakaway behaviour' began moved towards a lower dynamic load and it is speculated that this could be a result of a change in the friction force between the fuel and the pressure tube as the bearing pads 'wore in'.

During all of the above tests the outlet fuel bundle did not respond significantly.

CONCLUSIONS

The experimental fuel channel loop program has provided significant information to the investigation of the fuel failures at Darlington. The major conclusions from the program are as follows:

a) Fuel bundles potentially damaged through initial manual fuel loading do not behave differently to undamaged bundles.

b) Flow oscillations caused by the inlet end fitting geometry are unlikely to have caused severe inlet bundle fretting.

c) Flow causes the inlet bundle to move axially by about 3mm. The outlet bundle endplate deflects by between 0.5 and 1.0 mm with flow rate up to 30 kg/s.

d) Flow variations are unlikely to have caused the high cycle/low amplitude fatigue failures.

e) Pressure pulsations at high frequency (~ 150Hz) have been shown to cause end plate cracking, end plate/end plate, interelement spacer and bearing pad fretting. For end plate cracking the pressure pulse amplitude threshold is 25 - 40 kPa for GE fuel and about 65 kPa for ZPI fuel.

f) End fitting axial velocity provides a very rough estimate of the inlet end fitting pressure pulse amplitude but does not provide information on the bundle movement.

g) The feeder/fuel channel acoustics is very complex. Standing waves and travelling waves can exist throughout the system. A pressure node appears to always exist in the inlet end fitting.

h) The fuel does not respond significantly to external mechanical vibration in the axial direction. However forced axial vibration of the inlet bundle has a threshold beyond which significant axial movement of the bundle occurs.

The experimental program continues to provide additional information to assist the understanding of the problems at Darlington NGS.

ACKNOWLEDGEMENTS

The experimental work and results outlined above were undertaken by many people. Programs at the four test facilities were managed by I.Oldaker AECL CANDU, E.Kohn OH, F.Dermarker DNGS Operations and M.Boyd OHRD. Many others were involved in actually carrying out the programs and contributing to the understanding of the results including G.Hadaller STERN Laboratories, K.Saari AECL SPEL, and J.Vissers GE (Canada).

FIGURES

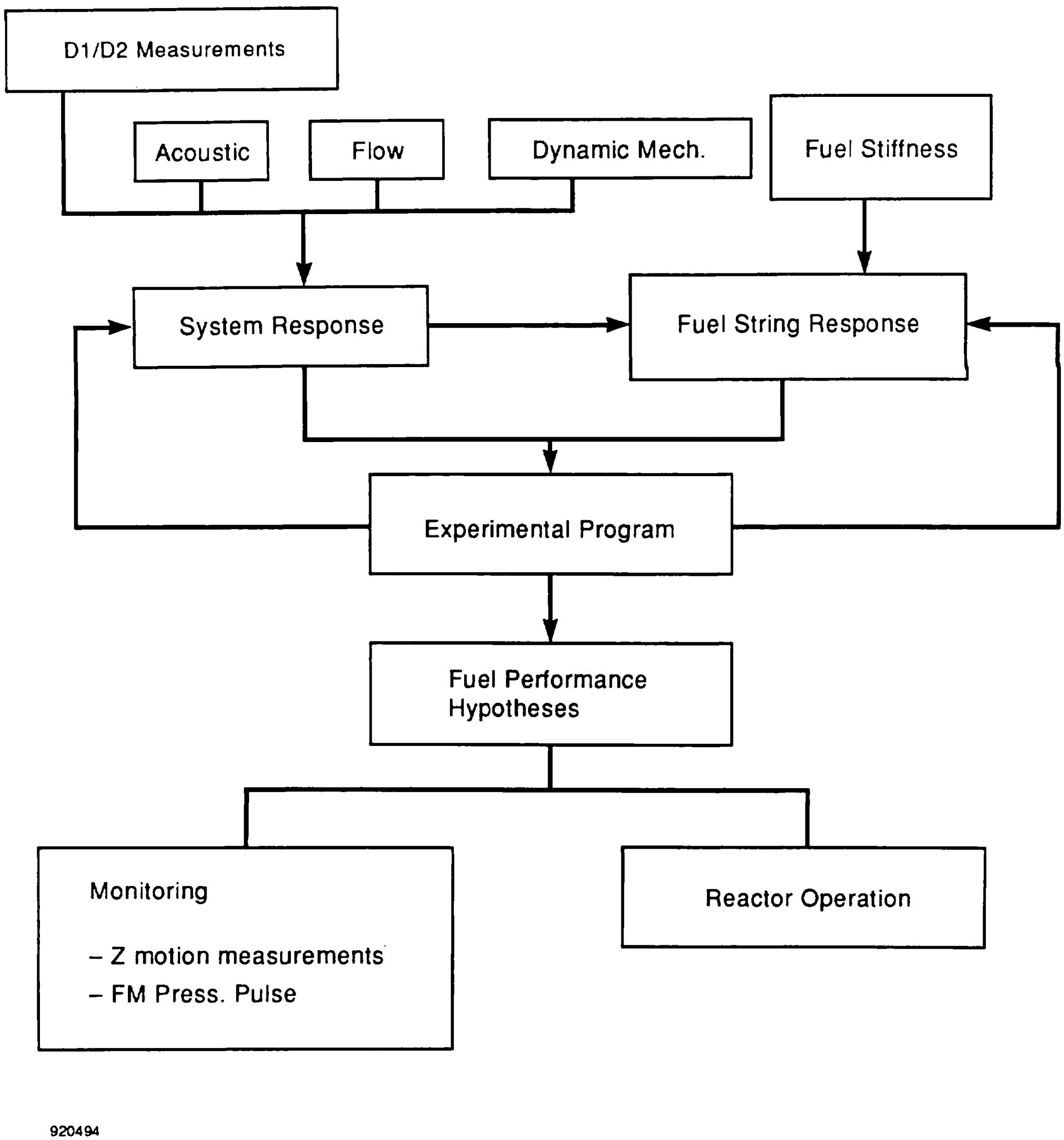

Figure 1
Relationship of the Experimental Program with Other Aspects of the Investigation

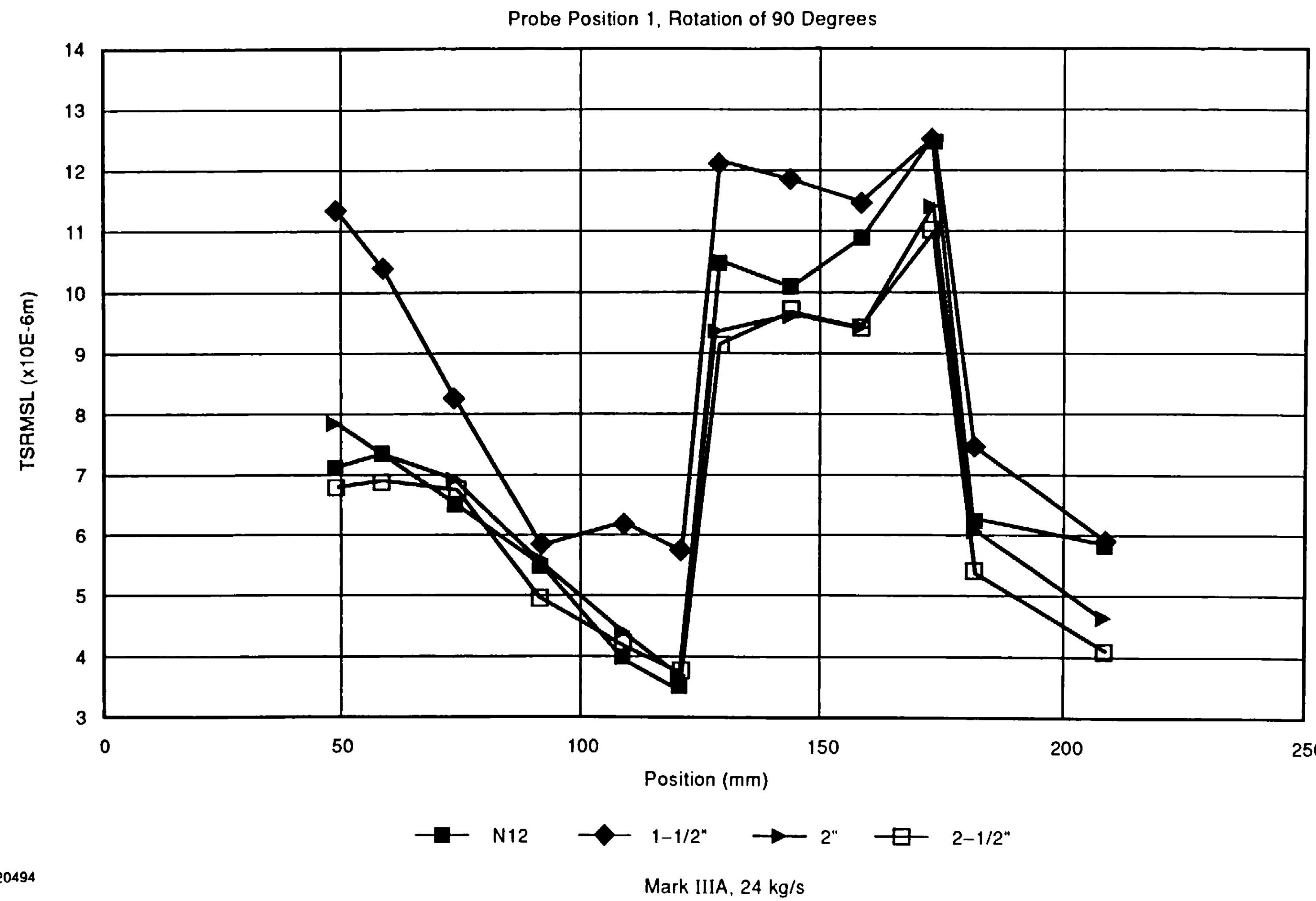

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Figure 2
'Rocking' of the Inlet Bundle with Inlet Geometry

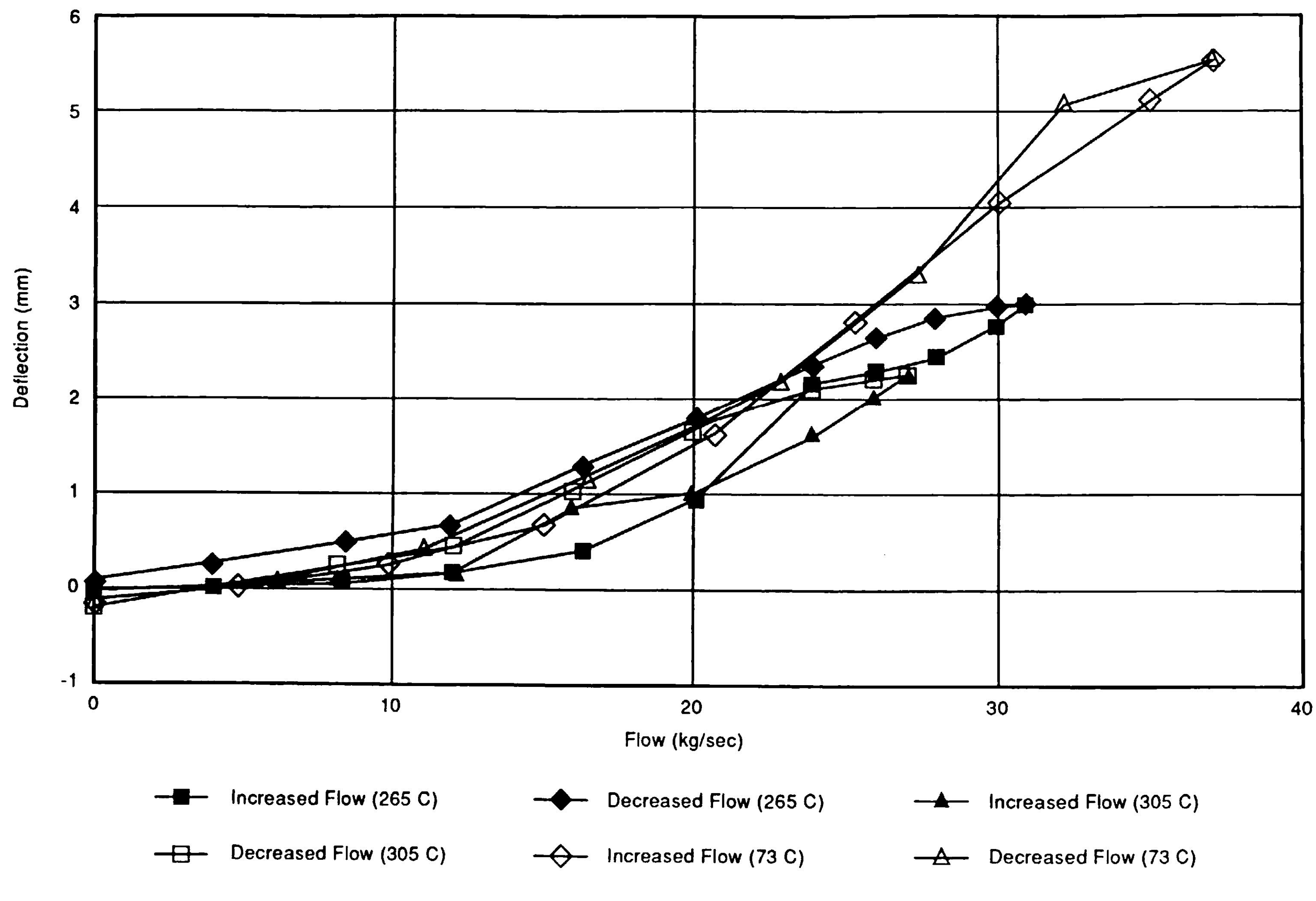

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Figure 3
Intlet Bundle Movement (Zircatec Fuel)

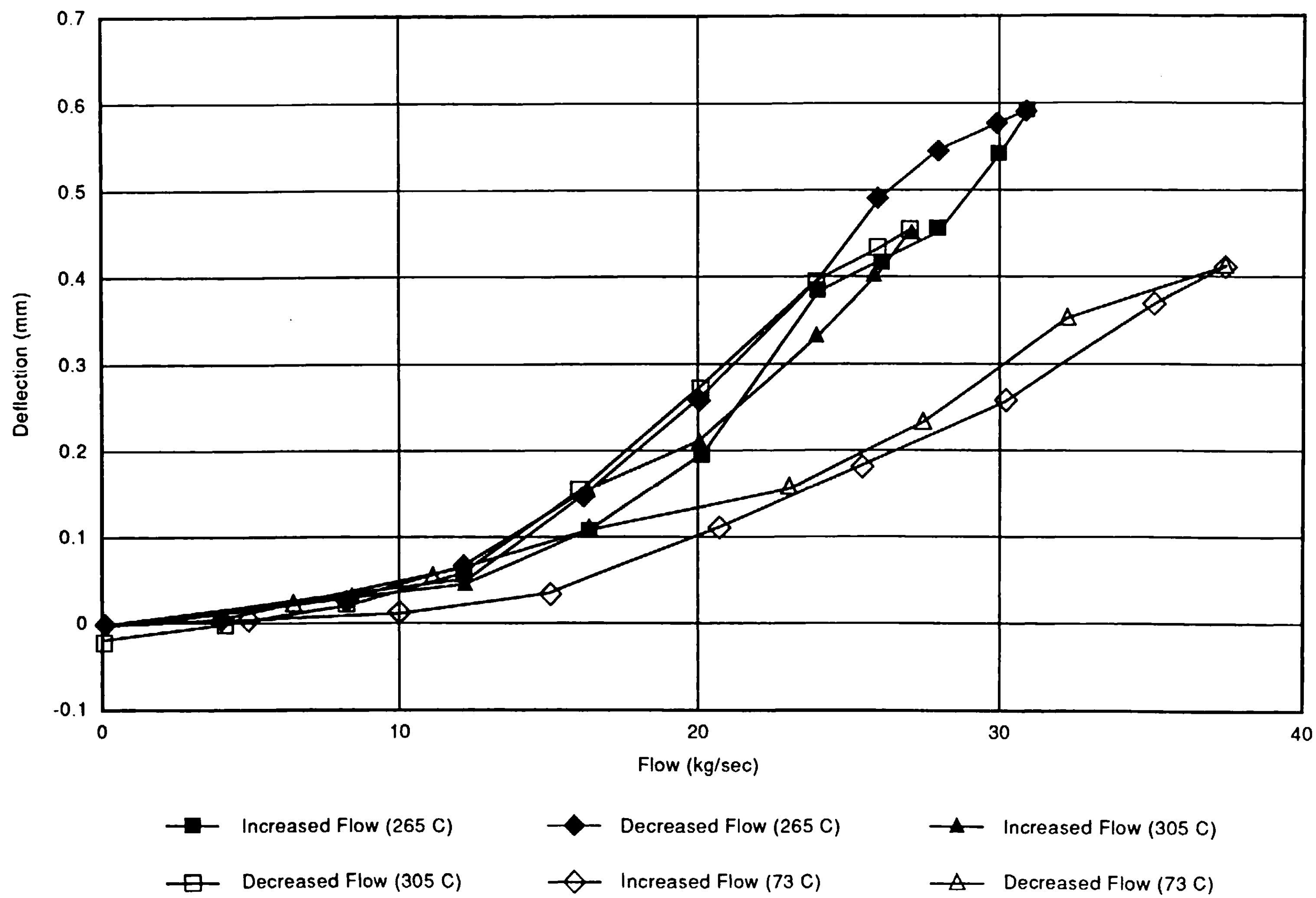

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Figure 4
Outlet Bundle Endplate Deflection (Zircatec Fuel)

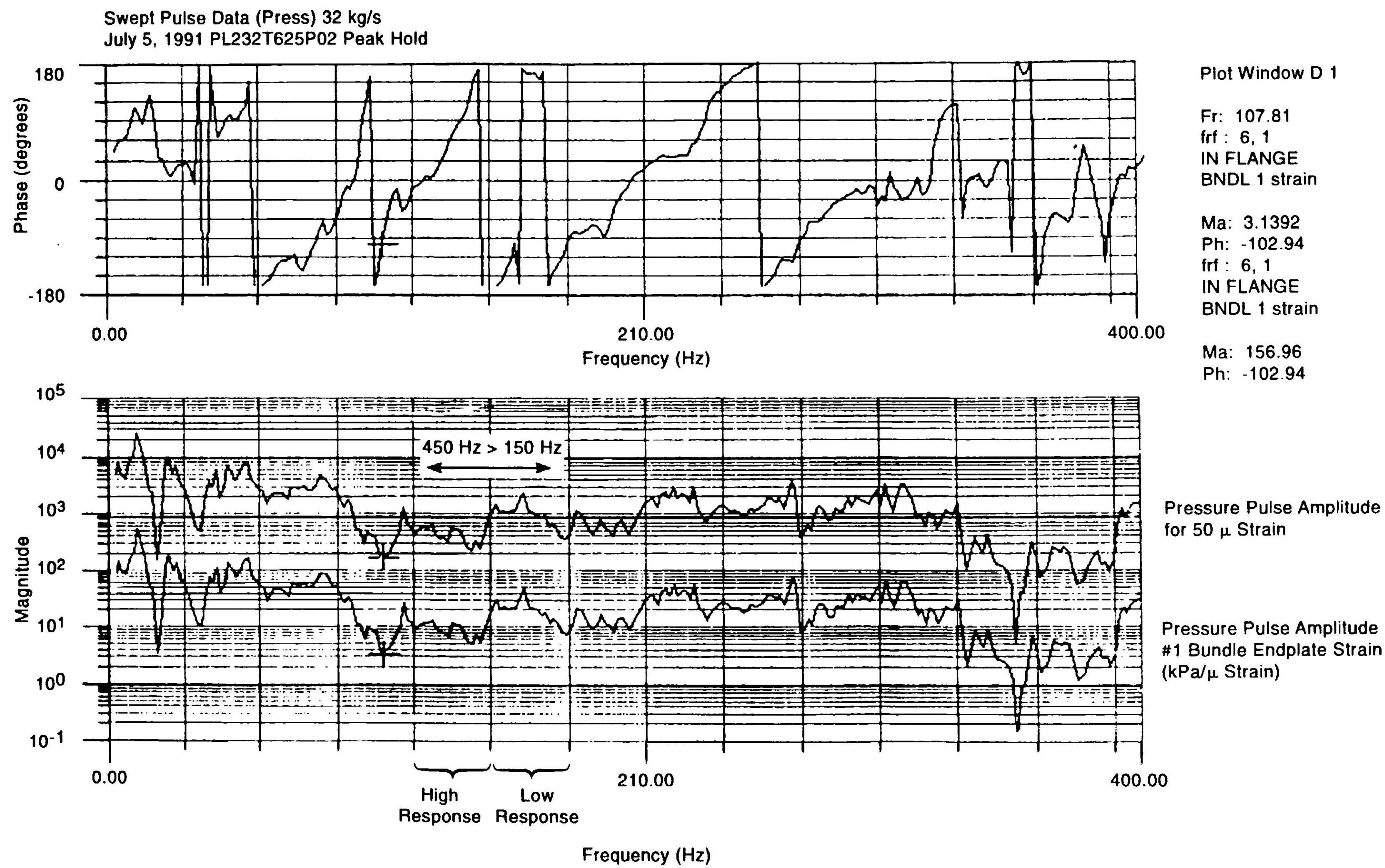

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Figure 5
Outlet Fuel Bundle Response to Frequency

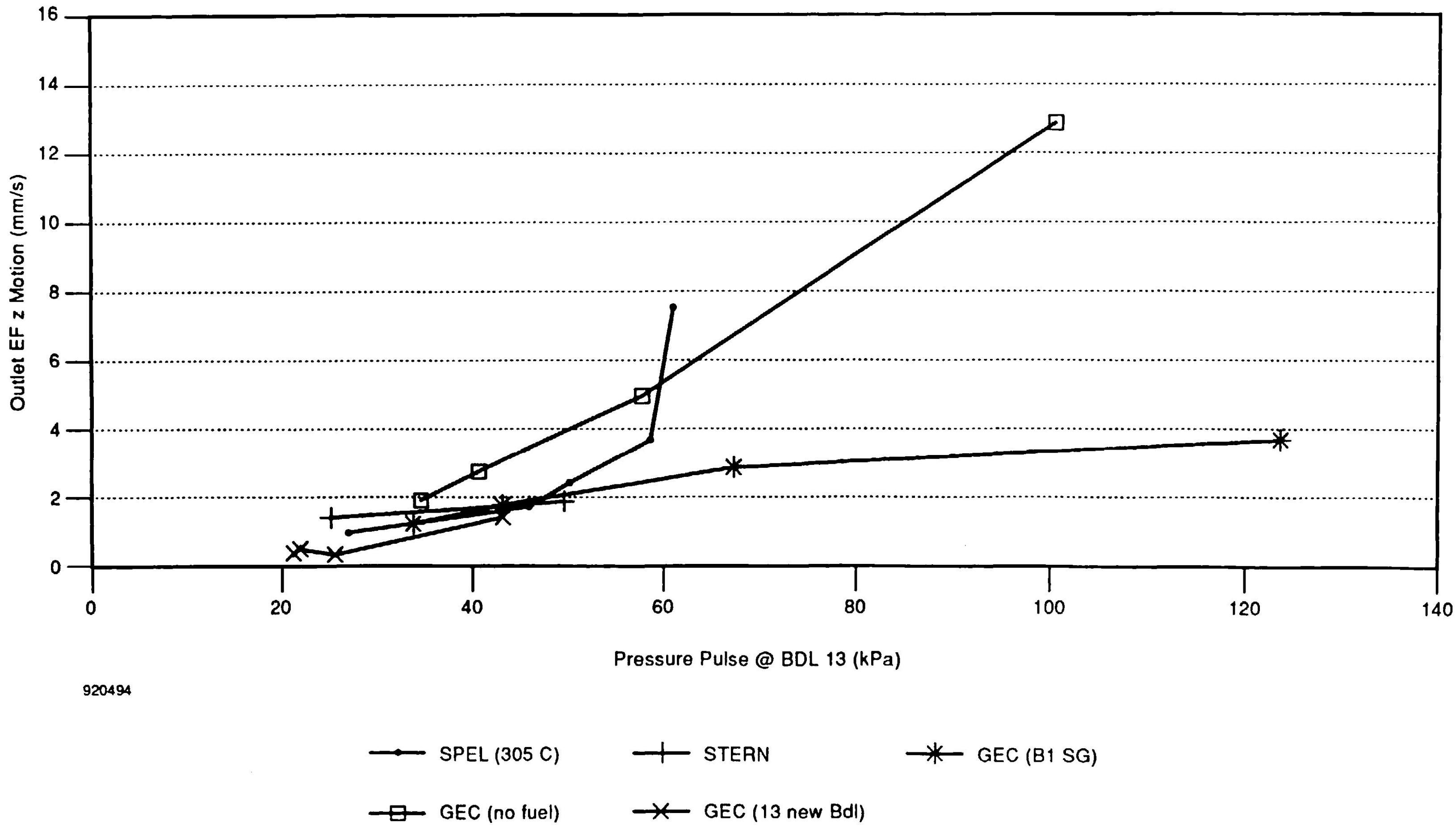

Figure 6
SPEL/STERN/GEC Out EF z mtn vs Pls @ Bdl 13 - 150 Hz Temp @ 295 C

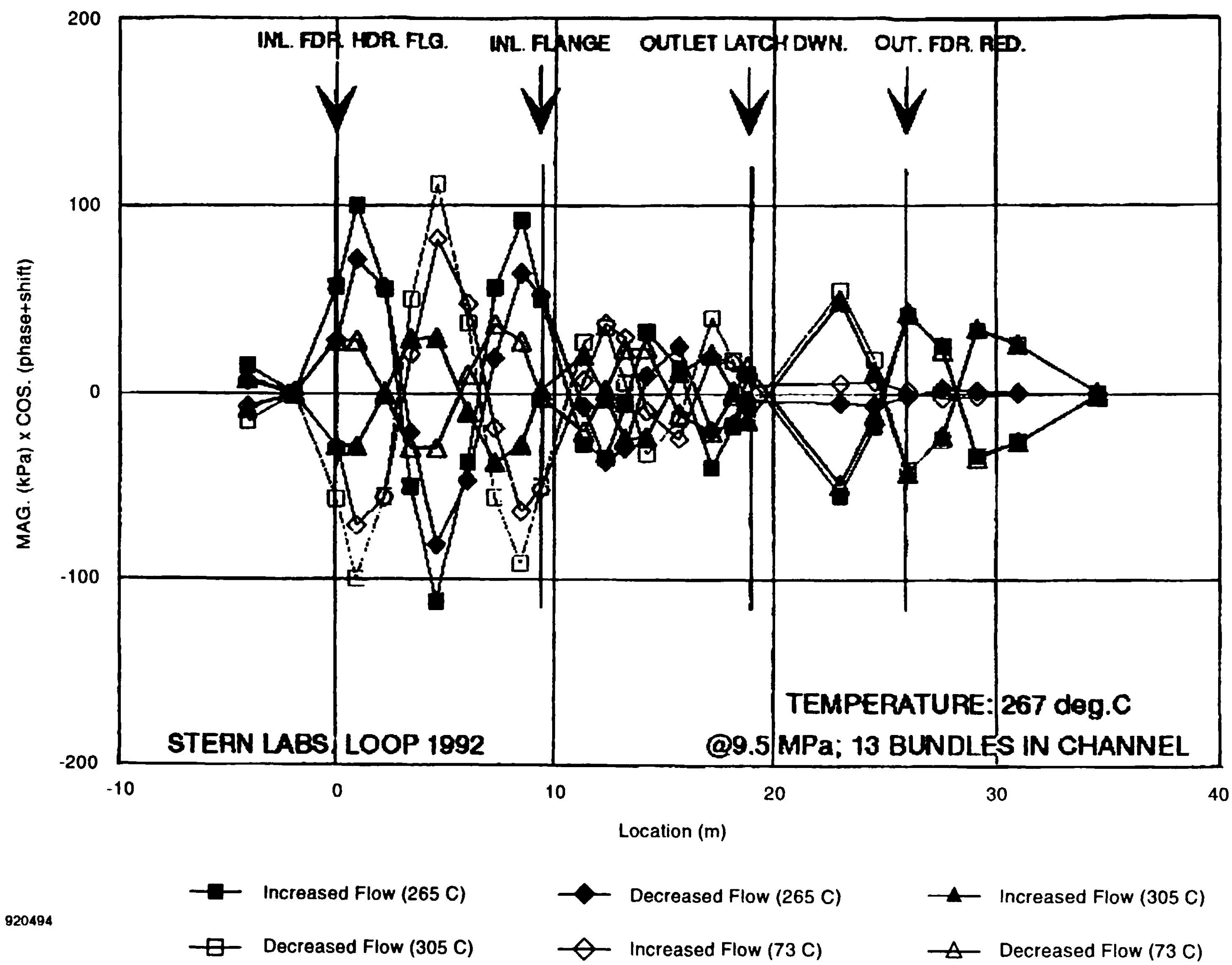

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Figure 7
Phase Shift for Tests HTPM 159 to HTPM 198 HTPM 189/150 Hz