DARLINGTON NGS A: SGECS CONDENSATION INDUCED WATERHAMMER ANALYSIS AND SGECS HOT COMMISSIONING TEST

for presentation to
20th Nuclear Simulation Symposium of the CNS
sponsored by the Canadian Nuclear Society

Niagara-on-the-Lake,
Ontario, Canada

September 7-9, 1997

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ABSTRACT

In the event of an accident such as the main steam line break, the Reheater Drain pump and the Feedwater pump could fail. As a result, feedwater to the steam generators (SG-1 and SG-3) will stop, and the inventory in the SGs flash. This would cause depressurization of the SGs and formation of steam void in the piping of the Steam Generator Emergency Cooling System (SGECS). The subsequent low SG pressure will initiate the SGECS injection into the SGs. Upon the injection of the cold SGECS fluid to the steam filled SGECS piping, condensation would take place, and condensation induced waterhammer in the SGECS may occur. As an interim measure to protect the SGECS piping, the Second Stage Reheater Drain flow to the SGs was suspended. This resulted in a 3% loss of power, a significant economic penalty to the heat cycle of the turbine.

To remove the economic penalty, the original design of the SGECS was revised. To ensure the adequacy of the revised design, condensation induced waterhammer analysis were performed for 6 design basis events. The predicted pressure transients were submitted for stress analysis and have passed the allowable level of stress limits.

The analysis was presented to the AECB. Although the AECB has accepted the analytical results, the AECB requested a 'hot' commissioning test at site to demonstrate that the revised design does meet the operation requirement.

The test was successfully performed. Subsequently, the AECB has allowed OH to re-instate the Second Stage Reheater Drain flow to the SGs.

1.0 INTRODUCTION

The original design of the SGECS is shown in Fig. 1. Its injection is to be gravity driven, and will be initiated as soon as the SG pressure drops to that of the SGECS tank.

There was a concern of condensation induced waterhammer in the SGECS (as shown in Abstract). As a result, the original design of the SGECS was analysed using the TUF code (OH's advanced Two Unequal Fluids thermohydraulic code). By stress analysis, the TUF pressure results showed SGECS pipe failure. To protect the SGECS piping, the 2nd Stage Reheater Drain (RHD) flow to the SGs was suspended. This resulted in a 3% loss of power, a significant economic penalty to the heat cycle of the turbine.

A plan of action was devised to mitigate the waterhammer potential of the SGECS. First, the original design of the SGECS was reviewed. The long pipe run leading to the dead end identified as contributor to waterhammer was shortened. This was achieved by check valve relocation in the SGECS line, the Inter Unit Feedwater (IUFT) line and the RHD line. To ensure the functioning of the check valves, another check valve was added in series with the original single check valve (Fig. 2). Then, using the revised SGECS piping arrangement, waterhammer analysis for 6 design basis events were performed, using an improved version of the TUF code. The pressure transient results for all cases were forwarded for stress analysis and have passed the allowable level of stress limits.

The AECB has accepted the analytical results.

However, the AECB requested a 'hot' commissioning test at site to demonstrate the revised SGECS capable of meeting the operation requirement.

The Reference Case (under normal operations) was used to design the test, and the test was successfully performed. The analytical results of the Reference Case and the test results were found to be in good agreement. Subsequently, the AECB has allowed OH to re-instate the 2nd Stage Reheater Drain flow to the SGs.

2.0 ANALYSIS METHODOLOGY

2.1 ANALYSIS SCOPE

The waterhammer analysis was performed for the SG-1/3 circuit, and the analysis covered 6 accident scenarios of design basis events, as follows:

- 1 Reference Case:

Case 1 - No check valve failure anywhere

- 5 Single check valve failure cases:

Case 2 - valve failed open at IUFT in SG-1 leg,
Case 3 - valve failed open at IUFT in SG-3 leg,
Case 4 - valve failed open at RHDL in SG-1 leg,
Case 5 - valve failed open at RHDL in SG-3 leg,
Case 6 - valve failed closed at SGECS line in SG-1 leg.

2.2 ANALYSIS ASSUMPTIONS

1. The SGECS piping was liquid-filled upstream of the double check valves, but steam-filled downstream.

2. Conservative assumptions were used to maximize the injection flow, and thus, the waterhammer effect for the analysis:

a. The SGECS tank pressure was constant at maximum achievable pressure of 820 kPa(g).

b. The check valves in the IUFT line and the RHD line were treated as dead ends. Leakage to dissipate the momentum of the SGECS injection was not considered.

c. The warm liquid front of the injection upstream of the double check valves in the SGECS line was not credited. In the actual system, the warm liquid front exists to diminish the waterhammer effect of the injection.

d. The temperature of the SGECS liquid was 20 °C, instead of 37 °C as in the actual system. Under this condition, the predicted waterhammer effect should be worse.

e. The 6 sec. dead time resulting from the activation of the valve was included in the analysis. This would result in a pressure drop of 30 kPa prior to the injection, and thus, increase the injection flow rate.

f. From the safety report, the SG was to be depressurized at about 5 kPa/s during the SGECS injection. This depressurization was used as a pressure boundary in the SGs. This would increase the pressure drop between the SGECS tank and the SG, and therefore, would increase the flow rate of the SGECS.

2.3 SIMULATION CONDITIONS

- Liquid Side:

- SGECS tank pressure: constant at 820 kPa(g)
- Liquid temperature: 20 °C

- Steam Side:

- The SGs were treated as steam tanks with pressure at 820 kPa(g). The steam was at saturation at 175 °C.

- A linear depressurization profile of 5 kPa/s was imposed on the SG as a pressure boundary. Taking the 6 sec dead time into consideration, the SG pressure profile was as follows:

Simulation Time (s)	Pressure (kPa(g))
0	790
60	490

- SGECS Control Valve:

- The control valve will be 92.5% opened in 7 sec and 100% opened in 14 sec.

2.4 TUF MODEL - SGECS

The SGECS piping circuit was nodalized into control volumes. In the liquid side, the nodes were about 1 to 1.5 m. long. In the steam side, the nodes were more refined, about 0.25 to 0.4 m., in order to capture the transient behaviour of the injection.

2.5 SIMULATION TIME STEP

The maximum time step used for the simulation is small, about 0.23 ms.

3.0 SIMULATION RESULTS

3.1 Case 1 - Reference Case

At the initiation of the SGECS, as soon as the control valves were opened, cold liquid from the SGECS tank was injected into the SGECS piping. At the T-junction near Check Valve NV38 (Fig. 2), the injection was split to fill the steam void at each of the SG legs. Due to the piping elevation, a greater portion of the SGECS liquid was initially drawn into the SG-3 leg (Fig. 3). After 4 seconds or so, the SGECS liquid has already filled the steam void in the IUFT line and the RHD line, and was moving towards the SGs at about equal flow rates of 20 kg/s. In another 10 seconds, the SGECS liquid has filled the entire piping including the ring headers inside the SGs. Thereafter, the SGECS liquid was injected into the SGs steadily, and waterhammer is no longer a concern for the SGECS.

The TUF simulation has shown insignificant pressure transients everywhere, even at dead end locations considered to be prone to waterhammer, e.g., the dead end of the IUFT line, and the dead end of the RHD line (Fig. 4, and Table 1).

3.2 Cases 2, 3, 4 and 5 - Single Check Valve Failed Open

If a check valve has failed open in the downstream side of the IUFT line or the RHD line, the pipe run leading to the dead end will be lengthened. This would increase the SGECS injection flow towards the dead end of the lengthened line, rendering this line more vulnerable to waterhammer.

The simulation results showed that this was indeed the case, as pressure spike was predicted at the pipe where the check valve has failed. The maximum pressure spike was 8.0 MPa, predicted at the RHD line in the SG-1 leg for Failure Case 4 (Table 1).

For the re-designed SGECS, the resident time of the pressure spike was rather short, just couple of milliseconds (Table 2). This is beneficial to the piping system as the dynamic stress load on the piping would last for a short duration only.

3.3 Case 6 - Single Check Valve Failed Closed

At the initiation of the SGECS, if one of the double check valves in the SGECS line is stuck closed, all of the SGECS liquid will be injected into the other SG leg.

In the case of check valve stuck closed in the SG-1 leg, the flow behaviour in SG-3 was predicted as shown in Fig. 5 As a result, a pressure spike of 4.86 MPa was predicted at the dead end of the IUFT line in the SG-3 leg. Insignificant pressure transients would occur in the rest of the piping (Table 1).

4.0 CONCLUSIONS

1. Conservative assumptions were used for the analysis to maximize the waterhammer effect of the SGECS injection. Under these assumptions, the results still meet the required level of stress limits.

2. For the Reference Case, the peak pressures developed at the dead end pipes were insignificant and were determined to be representative of the system.

3. For the failure cases, the peak pressures were conservative due to the use of conservative assumptions and the TUF code which produces conservative results.

4. The pressure transient results passed the stress analysis, indicating that the re-design of the SGECS is effective in reducing the waterhammer effect to acceptable stress levels.

5.0 RECCOMENDATIONS

1. Ensure the SGECS initiation pressure be close to that of the SGECS tank in order to prevent excessive flow during the SGECS injection.

2. Use temperature monitoring to maintain the fluid in the subcooled state at the upstream of the double check valves in the SGECS line in order to achieve the liquid condition in the SGECS line.

APPEDIX:

SGECS 'HOT' COMMISSIONING TEST

1.0 OBJECTIVES

The objectives are :

- to validate the design changes made to the SGECS,
- to demonstrate that waterhammer is not a concern for the SGECS injection

2.0 TEST CRITERIA

The test will last for no more than 3 minutes, and it must represent a real injection within design operating conditions. The stress level must not exceed Level B allowable stress limits.

3.0 RECORDING INSTRUMENTS

Based on the results of the SGECS waterhammer analysis, the recording instruments were installed in the SG-3 leg.

Recording Instruments used for the test:

a. Pressure Transducers
b. Accelerometers
c. Ultrasonic Flowmeter
d. Tape Recorder

4.0 TEST CONDITIONS - Analysis vs. Actual

The comparison is shown in Table 3.

5.0 TEST RESULTS

The test lasted just over 2 minutes. During this period, the SGECS tank level has dropped from 330 mm to 97.6 mm, and the liquid level has risen from 9.6 m. to 9.67 m. in SG-1, and from 9.6 m. to 9.68 m in SG-3. The SGECS did inject into SG-1 and SG-3.

a. Pressure Transients:

The pressure transients measured at 4 monitoring locations were insignificant (Fig. 6). The maximum pressure load was 400 kPa, developed upstream of the double check valves in the SGECS line.

b. Piping Movements:

The piping movemnets recorded by the accelerometer were insignificant.

c. Temperature:

The temperature has dropped soon after the initiation of the test, indicating that the SGECS injection reached this pipe location early in the test.

d. Flow

The ultrasonic flowmeter showed zero flow in most of the recordings, except for a flow spike of 6 l/s at about 97 sec.

6.0 CONCLUSIONS

1. Based on the SG level measurement, the SGECS did inject into each of the two SGs.
2. During the test, the accelerometers have recorded insignificant piping movements, implying that piping stresses were small. The stress analysis of the Reference Case has also shown SGECS piping stresses well within Level B Conditions. Thus, both the test and the analysis have demonstrated the safety aspect of the revised SGECS.

TABLE 1

ANALYSIS RESULTS - DARLINGTON SGECS MAX. PRESSURE (MPa) AT DEAD END PIPES

Case	Boiler 1 IUFT	Boiler 1 RHDL	Boiler 3 IUFT	Boiler 3 RHDL	Stress Level
1	1.20	1.17	2.24	2.00	B
2	**5.50**	1.10	2.30	1.50	D
3	1.61	1.40	**6.47**	1.49	D
4	2.80	**8.00**	2.09	1.62	D
5	1.19	1.10	3.80	**6.13**	D
6	0.89	0.89	4.86	1.37	D

N.B. Pressure in bold letters indicates where a check valve has failed open.

TABLE 2

Pressure Pulse Duration - Darlington SGECS SG-1/3 Circuit

Failure Case	Piping Location	Max. Pres. (MPa)	Pres. Pulse Duration (ms)
1	IUFT, SG-1	5.50	1.5
2	IUFT, SG-3	6.47	2.1
3	RHD, SG-1	8.00	1.2
4	RHD, SG-3	6.13	1.2

TABLE 3

TEST CONDITIONS vs. ACTUAL CONDITIONS

	Analysis	Actual
■ **Liquid Side:**		
- Tank Pres.(kPag)	820	762
- Liquid Temp.(°C)	20	36
- SGECS Tank Level (mm)	As a reservoir	Level at 330 mm
- Pressure in SGECS Line	820 kPa(g) +Elevation	Depres-surized
- Check Valve	On/Off by TUF	Valve Dynamic
■ **Steam Side:**		
- SG Pressure(kPag)	790	790
- Steam Temp.(°C)	175	175
- SG Pressure	-5 kPa/s	Constant
- SG Liquid Level	Below Ring Header	Below Ring Header

DARLINGTON SGECS (SG 1/3)
- ORIGINAL DESIGN -

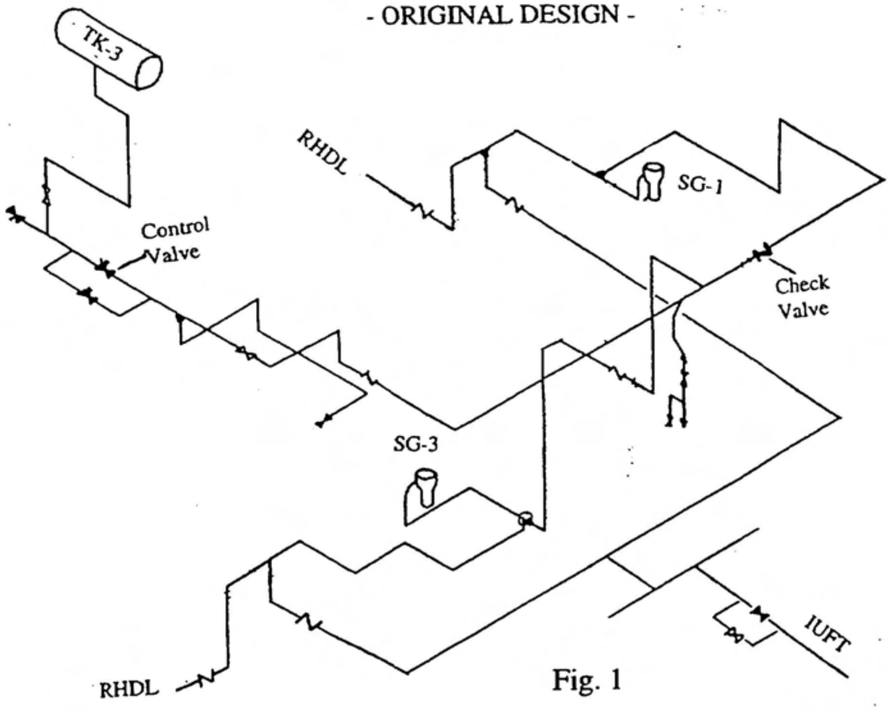
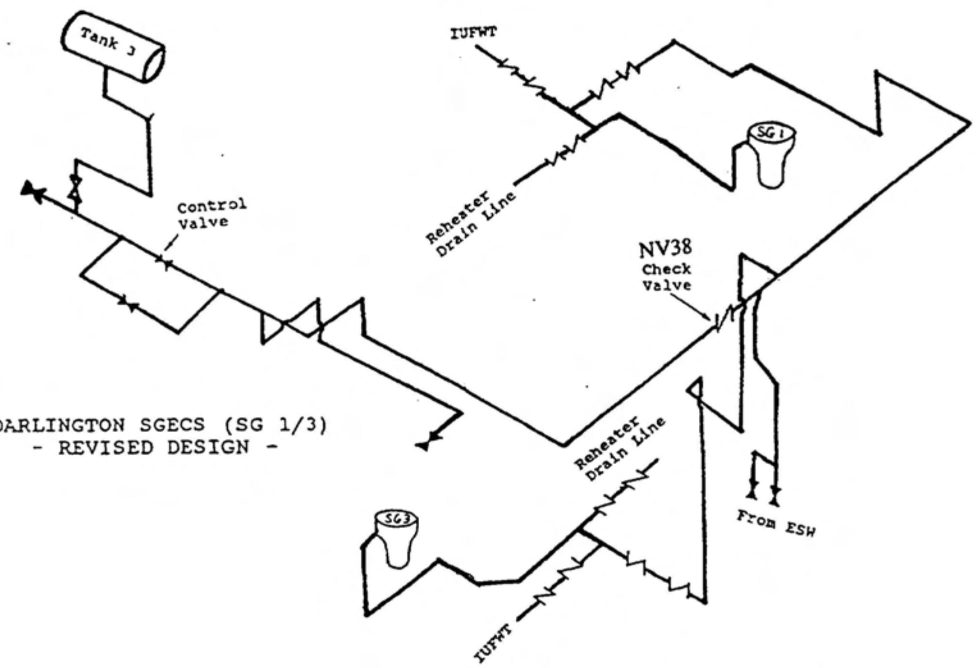
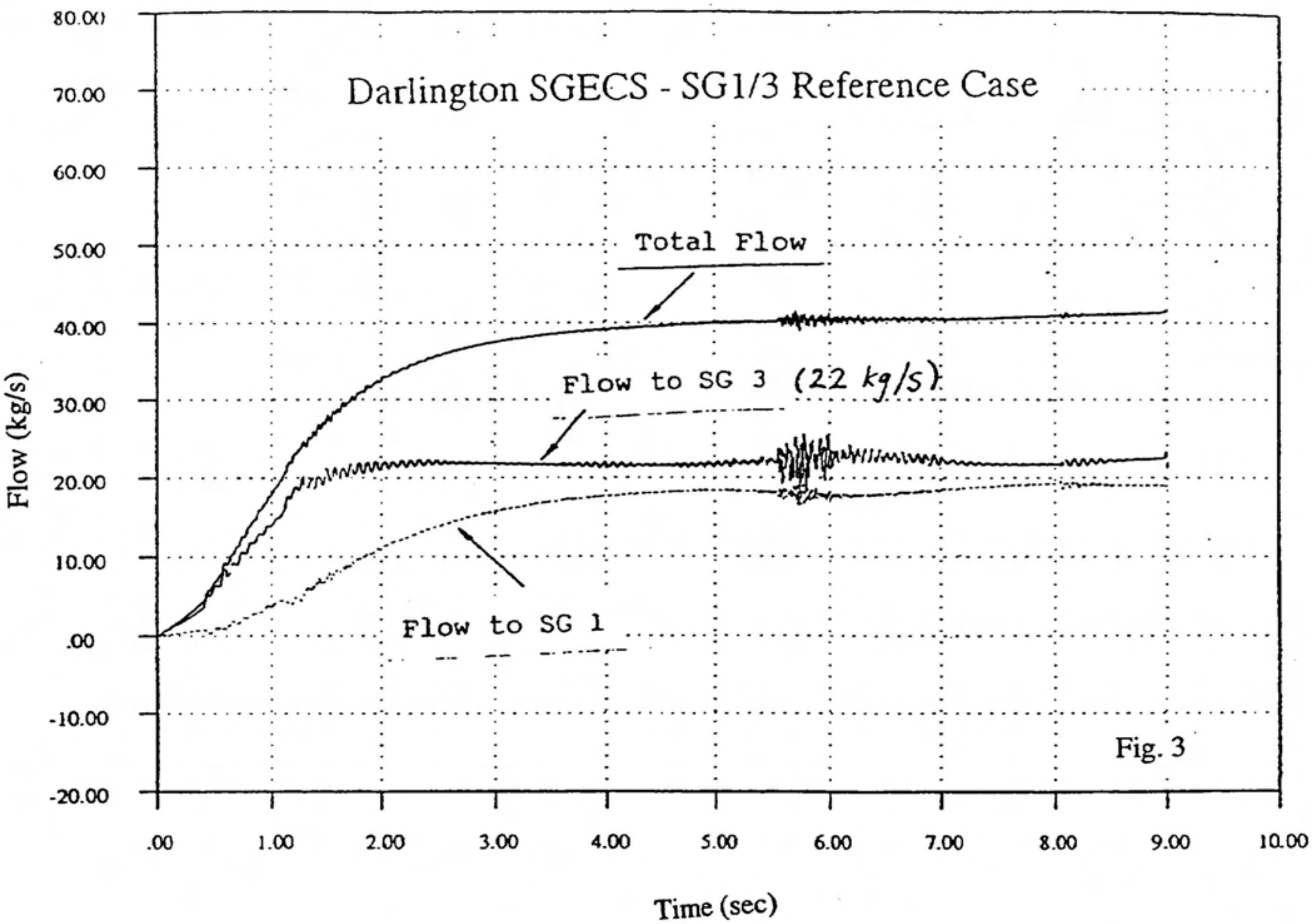


Fig. 1



DARLINGTON SGECS (SG 1/3)
- REVISED DESIGN -

Fig. 2


Darlington SGECS - SG1/3 Reference Case
Total Flow
Flow to SG 3 (22 kg/s)
Flow to SG 1
Flow (kg/s)
Time (sec)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
.00
-10.00
-20.00
.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Fig. 3

DARLINGTON SGECS SG-1/3 - REFERENCE CASE

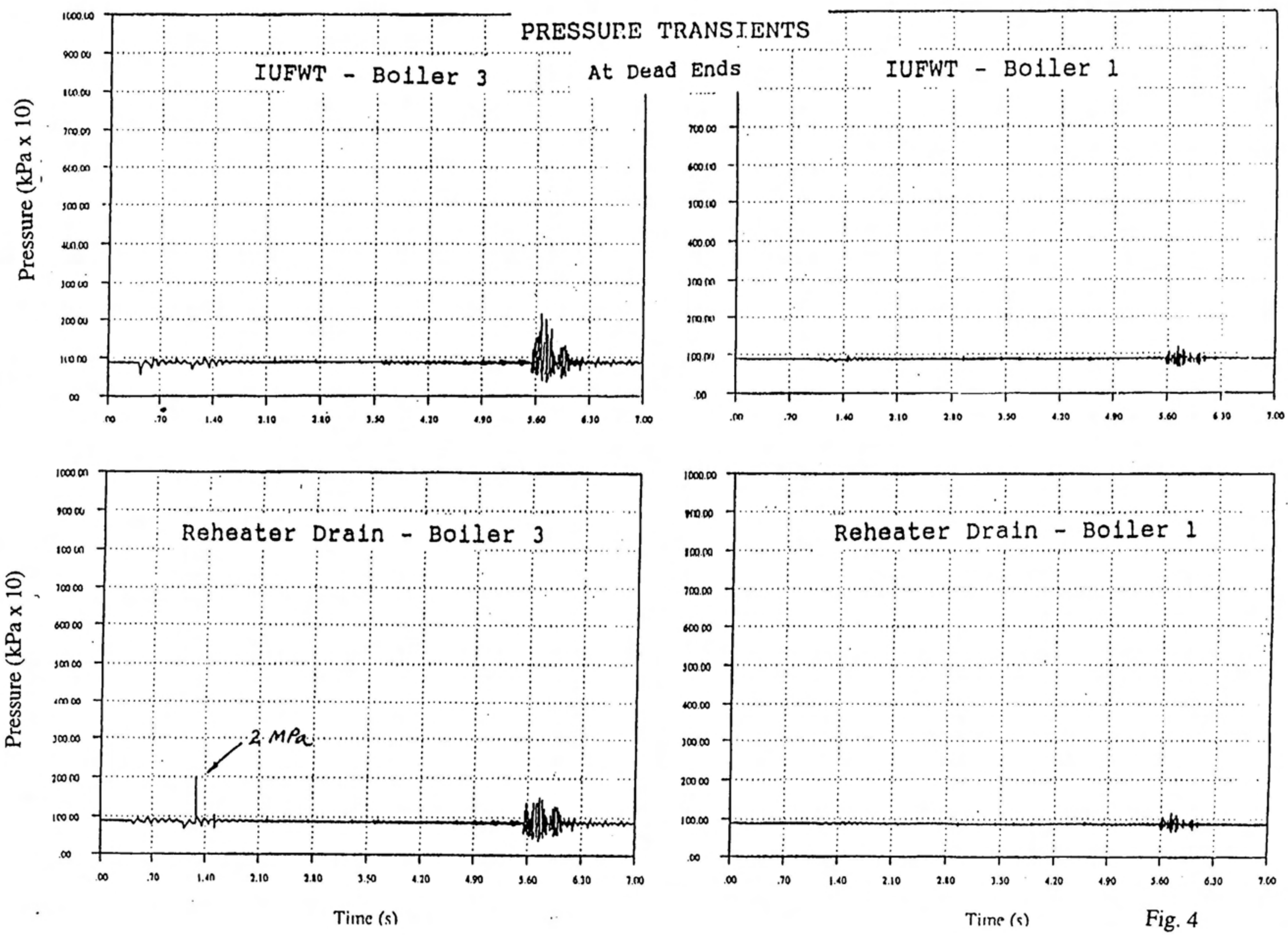


Fig. 4

DARLINGTON SGECS 1/3 - FAILURE CASE 6

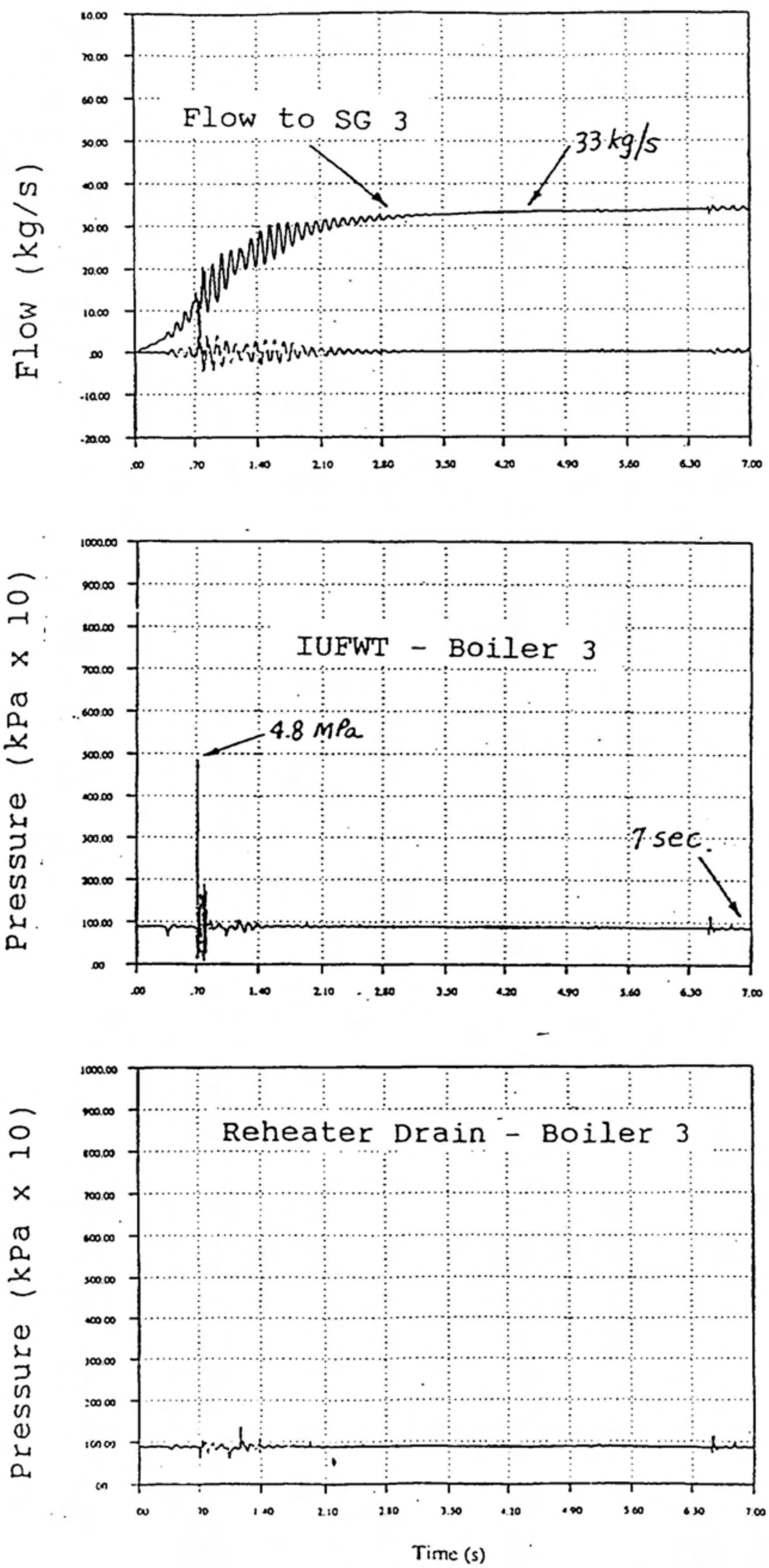


Fig. 5

PRESSURE TRANSIENTS - SGECS HOT COMMISSIONING TEST

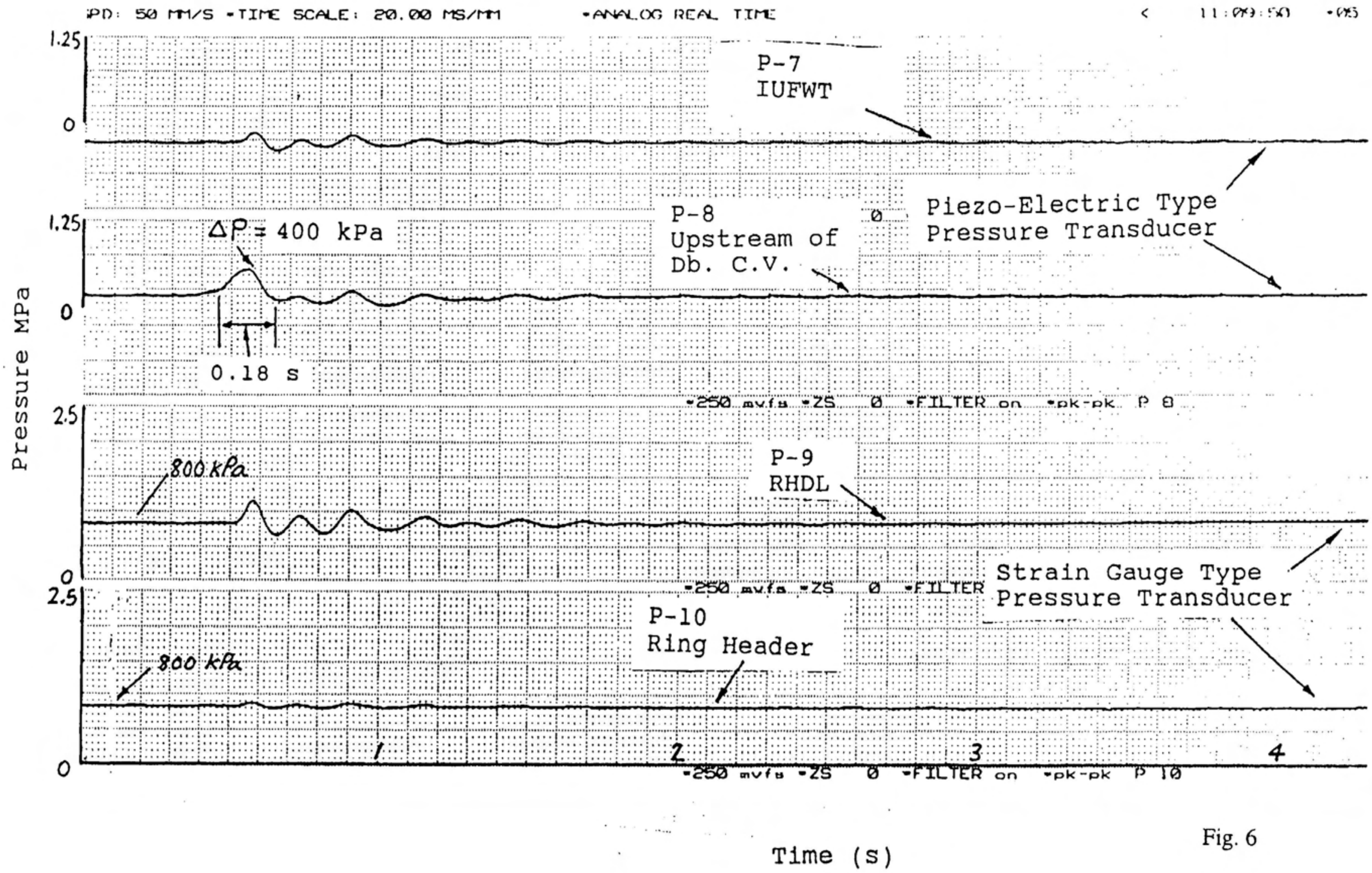


Fig. 6