

NON-EQUILIBRIUM FLASHING
IN A STEADY-STATE FLOW
OF ORGANIC COOLANT

by

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ABSTRACT

A test facility was designed and built to investigate the non-equilibrium flashing of a steady state flow of organic coolant through a ten foot long test section. As the fluid passed through the test section, its temperature, pressure, void fraction, and flowrate were measured at one foot intervals. Results of these measurements were used to determine the relationships between the pressure, temperature, void fraction, flowrate, superheat, and the non-equilibrium rate of vapour formation. All of the fluid properties behaved as expected, except at one location where the pressure and temperature of the fluid increased in the direction of flow. Evidence is provided to support the belief that this behavior was caused by a compression shock in the test section, and a discussion is presented to indicate the origin of this shock. Recommendations are given for additional studies that should be undertaken to support the information gained in this project.

TABLE OF CONTENTS

| | PAGE |
|--|------|
| 1. INTRODUCTION | 1 |
| 1.1 Nuclear Safety | 1 |
| 1.2 Monsanto HB-40 Organic Coolant | 5 |
| 1.3 Purpose of Project | 8 |
| 1.4 Relevance to Nuclear Safety | 11 |
| 1.5 Test Facility | 12 |
| 2. THE OFX TEST FACILITY | 15 |
| 2.1 General Description of the Test Facility | 15 |
| 2.1.1 Flow Diagram | 15 |
| 2.1.2 Injection Vessel TK1 | 20 |
| 2.1.3 Blowdown Vessel TK2 | 22 |
| 2.1.4 Pump P1 | 25 |
| 2.1.5 Heater HR1 | 25 |
| 2.1.6 Heat Exchanger HX1 and Spray Condenser CD1 | 26 |
| 2.1.7 Nitrogen Bubbler L53 and Nitrogen Purge L52 | 26 |
| 2.2 Arrangement of Test Section | 28 |
| 2.3 Control and Safety | 32 |
| 2.3.1 Heater Control | 32 |
| 2.3.2 Trips and Alarms | 34 |
| 2.3.3 Release Mechanisms | 35 |
| 2.3.4 Containment and Fire Precautions | 36 |

| | PAGE |
|---|------|
| 3. INSTRUMENTATION | 39 |
| 3.1 Temperature Measurement | 39 |
| 3.2 Pressure Measurement | 48 |
| 3.3 Volume Flow Measurement | 50 |
| 3.4 Mass Flow Measurement | 52 |
| 3.5 Void Fraction Measurement | 55 |
| 3.6 Auxiliary Instrumentation | 57 |
| 4. DATA PROCESSING | 61 |
| 4.1 Signal Conditioning | 61 |
| 4.2 Data Logging | 61 |
| 4.2.1 Computer Interface | 61 |
| 4.2.2 PDP-8/I Computer | 62 |
| 4.2.3 Accuracy of the Data Logging System | 63 |
| 4.3 Data Processing | 64 |
| 5. DATA | 66 |
| 5.1 Tests Conducted | 66 |
| 5.2 Representative Data Set | 68 |
| 6. DISCUSSION OF RESULTS | 71 |
| 6.1 Void Fraction | 71 |
| 6.2 Volume Flowrate and Slip Ratio | 74 |
| 6.3 Mass Flowrate | 78 |
| 6.4 Pressure and Temperature Profiles | 81 |
| 6.5 Martinelli-Nelson Correlation | 97 |
| 6.6 Value of β | 98 |

| | PAGE | |
|----------------|----------------------------|-----|
| 7. CONCLUSIONS | 103 | |
| NOMENCLATURE | 108 | |
| REFERENCES | 112 | |
| APPENDICIES | 115 | |
| Appendix A.1 | Calculation of Zeta | 115 |
| Appendix A.2 | Calculation of Slip Ratio | 119 |
| Appendix A.3 | Mass Flow Indicator | 122 |
| Appendix A.4 | Void Fraction Measurements | 132 |
| Appendix A.5 | Calibration Data | 153 |
| Appendix A.6 | Data | 155 |

LIST OF FIGURES

| FIGURE | PAGE |
|---|------|
| 1 Simplified Flow Diagram of the OFX Test Facility | 13 |
| 2 Plan View of the OFX Test Facility | 16 |
| 3 Detailed Flow Diagram of the OFX Test Facility | 17 |
| 4 Injection Vessel TK1 | 21 |
| 5 Blowdown Vessel TK2 | 23 |
| 6 Sliding Pipe and Blowdown Vessel TK2 | 24 |
| 7 Chromolox Heater HR1 | 27 |
| 8 Void Fraction Probe | 30 |
| 9 Test Section Spool Piece | 31 |
| 10 Plan View of Test Facility within Explosion Proof Containment | 37 |
| 11 Simplified Flow Diagram of the OFX Test Facility | 40 |
| 12 Thermocouples Attached to Heater Sheaths | 41 |
| 13 Thermocouple Locations in Injection Vessel TK1 | 43 |
| 14 Test Section Spool Piece | 44 |
| 15 Void Fraction Probe | 45 |
| 16 Turbine Flow Meter | 51 |
| 17 Level Transmitter on Injection Vessel TK1 | 54 |
| 18 Orifice Plate Flow Meter 2F | 58 |
| 19 Orifice Plate 2F | 59 |
| 20 Simplified Flow Diagram of the OFX Test Facility | 60 |
| 21 Void Fraction versus Distance | 72 |
| 22 Volume Flowrate versus Distance | 75 |

| FIGURE | PAGE |
|--|------|
| 23 Slip Ratio versus Distance | 77 |
| 24 Mass Flowrate versus Pressure in Vessel TK1 | 79 |
| 25 Mass Flowrate versus Temperature in Vessel TK1 | 80 |
| 26 Pressure versus Distance - Series 3 | 82 |
| 27 Pressure versus Distance - Series 4 | 83 |
| 28 Temperature versus Distance - Series 3 | 84 |
| 29 Temperature versus Distance - Series 4 | 85 |
| 30 Pressure versus Temperature - Series 3 | 88 |
| 31 Pressure versus Temperature - Series 4 | 89 |
| 32 Martinelli - Nelson Correlation - Series 3 | 99 |
| 33 β versus Distance | 100 |
| A.1 Two Stations Along the Test Section | 116 |
| A.2 Level Transmitter on Vessel TK1 | 123 |
| A.3 Time Response of Differentiator | 128 |
| A.4 Mass Flowrate (Calculated) versus Output from Mass Flow Indicator | 130 |
| A.5 Mass Flow Indicator (MF1) versus Turbine Flowmeter (1F) | 131 |
| A.6 Void Fraction Probe | 133 |
| A.7 Parallel Plate Capacitor showing Typical Incremental Capacitor | 135 |
| A.8 Impedance versus Frequency for a Parallel Plate Capacitor | 140 |
| A.9 Impedance Change caused by a Shift in the Resonant Frequency | 142 |
| A.10 Calibrating Arrangement for Void Fraction Meter | 144 |

| FIGURE | | PAGE |
|--------|---|------|
| A.11 | Void Fraction Meter VF1 Calibration Curve - 330 Degrees C. | 149 |
| A.12 | Void Fraction Meter VF1 Calibration Curve - 340 Degrees C. | 150 |
| A.13 | Void Fraction Meter VF1 Calibration Curve - 350 Degrees C. | 151 |
| A.14 | Void Fraction Meter VF1 Calibration Curves | 152 |

1. INTRODUCTION

1.1 Nuclear Safety

One of the most serious accidents that could occur during the operation of a large nuclear power plant would be a major rupture of the reactor primary circuit (ref. 2, 11, 15, 19). During normal operation of a nuclear power station, the primary coolant is either allowed to boil forming steam which drives a turbine, or passed through a heat exchanger where it transfers its heat to a secondary coolant (secondary circuit). This secondary coolant would then boil to produce the steam needed to drive the turbine.

The coolant in the primary circuit is at a high temperature and under high pressure, so should a rupture occur, the coolant would be forced out of the break into the surrounding environment, which is normally maintained at atmospheric pressure. This loss of coolant and the associated reduction in primary circuit pressure would result in partial voiding of the reactor core, thus leaving the hot nuclear fuel without adequate cooling. Due to the decay heat associated with nuclear fuel, the temperature of the fuel sheath could rise above its melting point. In water and sodium cooled reactors a chemical reaction could occur between the molten fuel

sheath and the coolant, allowing fission products to be released into the coolant causing serious radioactive contamination (ref. 11, 15).

Although the chances of these events taking place in a nuclear reactor are extremely small, it is important that the events and results be clearly understood. It is imperative to know how fast the core would be voided so that emergency core cooling could be introduced, and the reactor shut down in time to avoid a meltdown (ref. 2, 4, 15).

The nature of the events that would occur during such a process has been the object of intensive studies by most atomic power agencies and organizations (ref. 2, 3, 5, 10, 11, 13, 14, 16, 18, 19, 20). From the moment of rupture, a negative pressure wave would propagate into the primary circuit, and the coolant would begin to flow out through the rupture. When the pressure at the rupture dropped below the saturation pressure, some of the coolant would flash to a vapour. Thus, it would be a two-phase mixture flowing out through the rupture, which would discharge more slowly than a single phase liquid. Farther upstream the pressure would still be greater than the saturation pressure, so the coolant there would remain in the liquid state. As the

pressure continued to fall, more of the coolant would flash to a vapour and the discharge of coolant would be impeded still farther. Soon, choking* would occur, thus limiting the discharge rate.

It is very important that this maximum rate of discharge be known since it determines how quickly emergency devices must act to protect the reactor. Although the rate of discharge depends on many variables, perhaps the most important determining factor is the rate at which vapour forms as the pressure falls (ref. 12).

If the flashing process took place under equilibrium conditions, it would be a relatively simple matter to predict the amount of vapour formation that would accompany a reduction in pressure. An equilibrium flashing process could be established, for example, by heating stationary coolant in a pressurized, sealed vessel to near saturation conditions, and then reducing the pressure in very small increments. If the pressure was held constant after each small reduction until conditions had completely stabilized, then the liquid and flashed vapour

* Choking is the phenomenon of the maximum flowrate of fluid through an opening being limited by the area of the opening and the fluid conditions. When the flow is choked, the velocity at discharge is sonic, and cannot be increased farther.

would be in equilibrium with each other. For a single component fluid such as pure water, no vapour would form until the pressure dropped below the saturation pressure (corresponding to the liquid temperature). At that point all the liquid would vapourize. For a multi-component coolant such as an organic compound, a certain percentage of the coolant would vapourize when a particular reduction in pressure was experienced. This percentage could be determined experimentally (allowing equilibrium to be attained), or from theoretical considerations using the vapour pressure and Henry's Law constants of the various components.

When a fluid flows rapidly through a pressure reduction, such as occurs during a primary circuit rupture, there is insufficient time for the liquid and flashed vapours to come into equilibrium with each other. Consequently, equilibrium data and consideration would not apply to such conditions.

The non-equilibrium discharge of water from pipes and vessels has been very well investigated (ref. 2, 3, 5, 11, 12, 13, 14, 15, 18, 19, 20). Since water is a single component fluid, it is possible to describe the flashing process mathematically and thus predict the rate of vapour formation. On the other hand,

very little work has been done to investigate the non-equilibrium flashing of multi-component fluids. Because of the many components present in both the liquid and vapour phases, the flashing process becomes extremely complex. Not only does a temperature gradient exist in the liquid (because the bubble is cooled by latent heat of vapourization), but concentration gradients are also established because certain components will flash more quickly than others and will thus be depleted in the area directly surrounding the bubble. When flashing takes place under non-equilibrium conditions, these gradients do not have time to disappear, and it becomes a very difficult problem to predict the flashing rates.

1.2 Monsanto HB-40 Organic Coolant

The multi-component fluid chosen to be investigated was a heat transfer medium produced by Monsanto Limited, called HB-40. It is a partially-hydrogenated terphenyl which is composed of a complex mixture of components. When considering the flashing process, HB-40 may be divided into eight groups of components, and each group may be treated as a single component. Reactor grade HB-40 (used as a reactor coolant) has the following equilibrium concentrations of the eight

component groups:

| | | |
|---|-----|--------|
| water - - - - - | 500 | ppm. |
| hydrogen - - - - - | 40 | ml/kg. |
| methane - - - - - | 40 | ml/kg. |
| C ₂ - C ₅ * - - - - - | 40 | ml/kg. |
| volatiles** - - - - - | 2 | wt. % |
| biphenyls - - - - - | 5 | wt. % |
| intermediate boilers - - - - - | 63 | wt. % |
| high boilers - - - - - | 30 | wt. % |

It will be noted that the weight fractions of the last four component groups add up to unity. This is because the other four groups make an insignificant contribution to the total weight of the liquid. However, these lighter components do make a significant contribution to the flashing process, since they are the first to begin flashing. Different units were used for different groups to make the quantities more meaningful.

The composition of HB-40 coolant changes as it is subjected to the high temperatures and radiation fields within the reactor. The equilibrium concentrations are obtained after approximately two months of reactor operation. Fresh HB-40, before it has been used in the reactor, is composed of virtually one hundred percent intermediate boilers with fifty parts per million water. The HB-40

- * The C₂ - C₅ group includes all hydrocarbons which have the form C₂---, C₃---, C₄---, and C₅---
- ** The volatiles group includes all hydrocarbons in the C₆ - C₁₂ group.

used for the present project was found to have the following concentrations of the eight component groups:

| | | | |
|---------------------------------|-----------|-----|--------|
| water | - - - - - | 350 | ppm. |
| hydrogen | - - - - - | 0 | ml/kg. |
| methane | - - - - - | 0 | ml/kg. |
| C ₂ - C ₅ | - - - - - | 20 | ml/kg. |
| volatiles | - - - - - | 2 | wt. % |
| biphenyls | - - - - - | 5 | wt. % |
| intermediate boilers | - - - - - | 93 | wt. % |
| high boilers | - - - - - | 0 | wt. % |

Organic liquids have been in use since 1965 as the primary coolant in the research reactor WR-1 located at the Whiteshell Nuclear Research Establishment of Atomic Energy of Canada Limited at Pinawa, Manitoba.(ref. 1). Although WR-1 is the only organic cooled reactor currently operating in the world, organic cooled reactors have several significant advantages over the more popular water cooled reactors (ref. 7). HB-40 has a very low vapour pressure and therefore can be used at higher temperatures than water (resulting in higher efficiency), but does not require high pressure structures. Also, HB-40 is not corrosive and hence corrosion products would not be carried into and out of the reactor core. For this reason, the primary circuit of an organic cooled reactor would be virtually free from radioactive contamination, which would mean much easier maintenance (ref. 7).

The difference between (dX/dP) and $(dX/dP)_e$ was due solely to the fact that during the non-equilibrium process, temperature and concentration gradients were established in the fluid. In the equilibrium process time was available for these gradients to disappear.

Zeta may be thought of as a measure of the non-equilibrium character of the flashing process. The change in quality with pressure (dX/dP) was a difficult property to measure in a non-equilibrium process; however, it may be shown (see appendix A.1) that the liquid superheat:

$$(T - T_{SAT})$$

was an equivalent indication of the non-equilibrium nature of a flashing flow. Since the liquid superheat was easier to measure than zeta, and since it could be used to calculate (dX/dP) directly, the superheat was a more satisfactory measure of the departure from equilibrium.

The non-equilibrium flashing process was established by allowing heated HB-40 to discharge through a test section into a vessel maintained at a pressure below the saturation pressure of the liquid. Secondary objectives of this project were to determine the mass flowrate of coolant through the test section, and to

determine the pressure gradient along the test section. The measured pressure gradient was also to be compared with the prediction of the Martinelli - Nelson model.

The main objectives of the project may be stated as:

a). To measure the liquid superheat ($T - T_{SAT}$), where T_{SAT} is defined as the saturation temperature corresponding to the measured pressure, as a function of:

- dP/dL (the pressure gradient along the test section)
- P (the pressure of the fluid at the position and time of interest)
- α (the void fraction of the fluid at the position and time of interest).

b). To determine the pressure gradient along the test section and compare it with the predictions of the Martinelli - Nelson model.

c). To determine the mass flow rate as a function of:

- dP/dL (the pressure gradient along the test section)
- $(T - T_{SAT})$ (the liquid superheat).

d). To determine the slip ratio* as a function of:

- dP/dL (the pressure gradient along the test section)
- α (the void fraction of the fluid at the position and time of interest).

* The slip ratio is defined as the ratio of vapour velocity to liquid velocity.

The ability of the computer programs to predict blowdowns with increased accuracy will allow for more accurate design of safety systems. Better estimates will be available of the speed with which the reactor must be shut down and emergency core cooling introduced. In general, these programs will be able to give better information which will result in the design of safer nuclear power stations. In addition, the information provided on the behavior of HB-40 during blowdown will assist in the design of organic cooled reactors to meet the safety criteria of the nuclear reactor licencing authorities.

1.5 Test Facility

To investigate the blowdown behavior of organic coolants, a test facility was constructed to establish a steady-state, non-equilibrium flashing of HB-40. A simplified flow diagram of the facility is shown in figure #1, page 13. The pressurized coolant stored in vessel TK1 was passed through the heater HR1 where it was heated to near saturation conditions. Once the temperature had stabilized, the liquid was allowed to discharge through an instrumented test section L3 into a second vessel TK2 maintained at atmospheric pressure. As the HB-40 proceeded along the test section, its

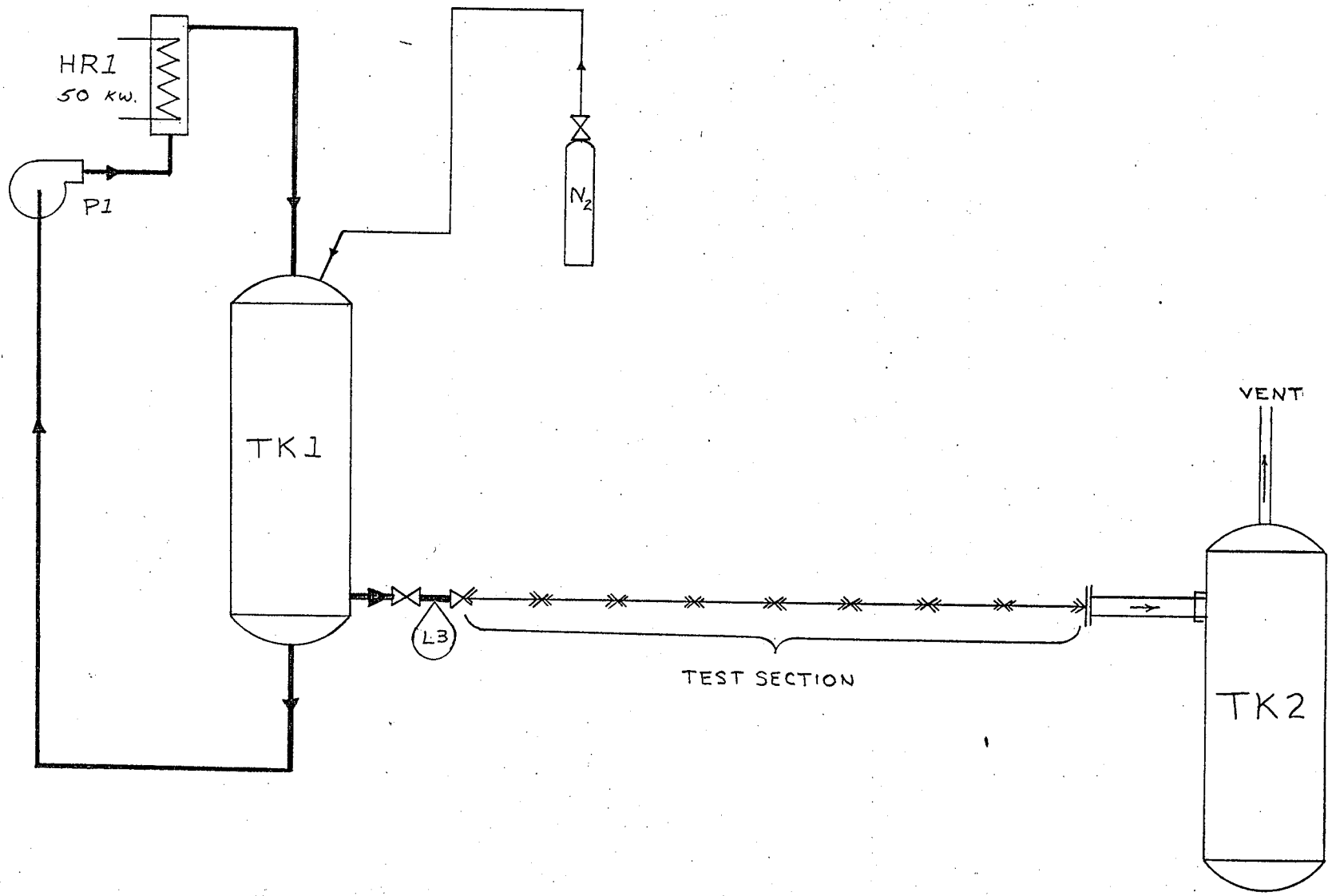


Figure # 1 Simplified Flow Diagram of the OFX Test Facility

pressure would drop. Once the pressure fell below the saturation pressure (corresponding to the liquid temperature) part of the liquid would flash to a vapour and a two-phase mixture would exist for the remainder of the test section. As the coolant proceeded farther down the test section, more liquid would flash to a vapour causing the void fraction to continuously increase with distance along the test section. By maintaining the pressure constant in the pressure vessels, steady state would be reached, and the conditions at any given point in the test section would remain constant with time.

Instrumentation, located along the test section and in the vessels could then be used to determine all of the relevant information. The required measurements were:

- a). the pressure in both vessels and at several stations along the test section (this provided dp/dL),
- b). the temperature in both vessels and at several stations along the test section (this gave the ~~superheat~~, superheat),
- c). mass and volume flow rates through the test section (used to determine the slip ratio and mass flow characteristics),
- d). the void fraction profile along the test section (needed as one of the correlating parameters).

2. THE OFX TEST FACILITY

The test facility described above shall now be examined in greater detail. Known as OFX, the facility was constructed at the Whiteshell Nuclear Research Establishment of Atomic Energy of Canada Limited, Pinawa, Manitoba. A plan view of the test facility is shown in figure #2, page 16.

2.1 General Description of the Test Facility

2.1.1 Flow Diagram

The operation of the test facility may be best understood by referring to the detailed flow diagram, figure #3, page 17.

In preparation for a test, the subcooled liquid stored in the injection vessel TK1* was drawn from that vessel by the pump P1, passed through the heater HR1 and back into vessel TK1. The liquid continued to circulate until it was stabilized at the desired temperature. Nitrogen gas was used, through a pressure regulator PRS1, to maintain the coolant under the desired pressure.

* In figure #3 all identification labels are preceded by OFX-