quantities of ice had again formed on the interface between the horseshoe valve and the poppet; free flow was evidentally caused by high overbottom pressure. Work of breathing did not vary from previous non-freezing analysis.

10. U.S. DIVERS PRO DIVER (total of 3 separate runs conducted under acceptable test conditions)

a. Successful: 0 runs

b. Minor malfunction: 0 runs

c. Major malfunction, evaluation stopped: 3 runs . In all three cases regulators went into severe free flow when first stage supplied with high pressure air.

d. Initial first stage overbottom pressure after freezing: Preset pressure was 140 psig. During these three evaluations accurate first stage pressures could not be attained. The regulators were subsequently monitored in a static condition, pressures recorded were at 200, 200, 220 psig.

e. First stage intermediate pressure control during one hour immersion/Analysis of Malfunction: In all three cases first stage overbottom pressure had risen to such an extreme as to immediately over power the dynamically balanced second stage valve.

f. Observation/analysis of malfunction: Regulator malfunction was directly attributed to high first stage intermediate pressures.

V. DISCUSSION

A. Comparison Evaluation U.S. Divers Cotton Backed and Nylon Backed First Stage Diaphragms. Subjective and objective test results clearly indicated that the cotton backed diaphragm became far less rigid than nylon backed units and as such had far less affect in raising USD CONSHELF XIV first stage static overbottom pressure above preset pressures for regulators exposed to cold environments. Pressures recorded from nylon units would have been more than sufficient to immediately over-drive dynamically balanced second stage demand valve into free flow.

B. Breathing Resistance/Work of Breathing. Data indicated that in all cases, whether dealing with conversion kits for diaphragm or silicon injection for piston first stages, that such configuration reduced the performance of the regulator as measured at 70°F. As depth and RMV levels increased, regulators equipped for cold water function had inhalation resistance and work of breathing values higher in comparison to their normal configuration. Analysis of volume vs. ΔP XY loops consistently showed an increase in area on the inhalation side. This larger area directly corresponds to an increase in work of breathing. The SCUBAPRO MK X/G-250, a first stage piston regulator, was the least affected in comparison to the remaining regulators equipped with diaphragm first stages. No further increase in work of breathing was noted when converted regulators were subsequently tested in the freezing environment. The work of breathing goal of .14 kg·m/ℓ (1.4 j/ℓ) at all depths

and RMVs up to and including 198 FSW on 62.5 RMV with 1000 psig supply pressure to the first stage regulator could not be attained by POSEIDON CYKLON 5000, POSEIDON ODIN, POSEIDON THOR, U.S. DIVERS CONSHELF SE2 and U.S. DIVER PRO DIVER. The goal was attained by the AGA DIVATOR MK II with AGA mouthpiece/USD ROYAL SL first stages and the SCUBAPRO MK X/G-250. However, in all cases exhalation/ inhalation values were well within the established values of the Mil Spec MIL-R-241698-SH 22 Feb 1982, reference (e).

C. Cold Water Function

1. First stage external spring cavity freeze. Use of environmental cold water conversion kits and silicon grease injection

a. The cold water conversion kits used on the diaphragm first stage regulators proved to be totally effective in preventing first stage exterior freeze of the spring cavity. No exterior freezes of diaphragm first stage regulators were recorded.

b. Environmental silicon grease injection proved to be effective in preventing spring cavity freezing. However, one case of first stage exterior freeze was recorded with SEA SPORT ZEPHER ZR-01. In this case silicon grease had been forced out of spring cavity through the first stage ambient sensing ports by piston action. Water entered the resulting void and a freeze occurred. All piston first stage regulators that used environmental protective silicon grease were checked for extrusion prior to each evaluation and silicon injected as necessary. The extrusion of silicon grease is a common problem with piston regulators. It can be limited, but not prohibited, via the adaptation of smaller ambient sensing ports as found on the SCUBAPRO MKX environmental standard silicon protection environmental cap.

c. The dry air bleed system utilized on the SHERWOOD MAGNUM BLIZZARD also proved totally effective in protecting its first stage from spring cavity freeze.

2. First stage interior freeze. No occurrence of first stage interior freeze was recorded, even though the average water vapor content in the supply air remained relatively high with a mean dew point of -40°F/-40.0°C/moisture content of 120 ppm, .089 mg/l.

3. First stage intermediate pressures

a. First stage intermediate pressure immediately after freezing: Relatively excessive first stage intermediate static pressures were recorded with AGA DIVATOR II with USD ROYAL SL first stage and the US DIVER PRO DIVER also equipped with the ROYAL SL first stage. The AGA breathing valve, a balanced pilot second stage, never went into free flow. However, the U.S. DIVERS PRO DIVER second stage, a dynamically balanced down stream poppet valve went into free flow on every evaluation. The ROYAL SL first stage did have cotton diaphragms installed, but its performance after freezing was not as controlled as the USD CONSHELF (XIV) first stage used with the USD SE2. All other first stage regulators static pressures remained near preset standards.

The most precise intermediate static pressure control consistent to preset pressures was demonstrated by the SHERWOOD MAGNUM BLIZZARD.

b. First stage intermediate pressure control during one hour immersion: Once the breathing machine was started all first stage intermediate pressure returned to optimum, with the exception of the SEA SPORT ZEPHER ZR-01. In this case intermediate pressure increased to 175 psig from a preset value of 150 psig, shortly thereafter the regulator malfunctioned with the first stage freezing and the regulator attained free flow.

The AGA DIVATOR MK II/USD ROYAL SL, POSEIDON CYKLON 5000, ODIN, and THOR; SHERWOOD BLIZZARD, all continued to operate within preset first stage pressure ranges.

The US DIVER SE2 operated normally but on one instance pressures increased to a maximum of 190 psig, then dropped and maintained at 170 psig, this coincided with the occurrence of a slight free flow, but the evaluation was completed. The SCUBAPRO MK X/G-250 and TEKNA 2100 BX both consistently increased their overbottom pressure with MK X/G-250 rising to a maximum of 174 psig and TEKNA to 190 psig. The design characteristics of both second stages (the SCUBAPRO a balanced adjustable, the TEKNA a pilot) prevent the second stages going into free flow as a direct result of excessive first stage overbottom pressures.

4. Second stage failure

a. Second stage failure, due to excessively high first stage overbottom pressure: The U.S. DIVERS PRO DIVER was the only regulator specifically identified as having malfunctioned due to excessive first stage pressure. The US DIVER CONSHELF SE-2 (identical second stage to the PRO DIVER) did attain a slight free flow as previously mentioned where pressure went as high as 190 psig. However pressures returned to 170 psig and the regulator completed the evaluation without attaining a severe free flow.

b. Second stage failure, due to freezing of valve assembly: The POSEIDON 5000 (one occurrence), the SCUBAPRO MK X/G-250 (two occurrences), SEA SPORT ZEPHER ZR-01 (two occurrences), TEKNA 2100 BX (two occurrences) and US DIVER CONSHELF SE-2 (three occurrences) could be identified as having failed due to icing on second stage demand valve mechanisms. Specific cause, whether by condensed water vapor, residual moisture, humidified exhaled gas, etc. could not be precisely determined; however, both the SCUBAPRO MK X/G-250 and U.S. DIVERS SE-2 second stages had ice form on demand diaphragms in the area immediately adjacent to the exhaust valve and in the case of the SE-2 on the interior surface of the exhaust valve. This would tend to suggest some moisture may have entered due to splash back from the exhaust valve.

5. Performance in cold water based on second stage design features

a. Unbalanced/dynamically balanced demand poppet [POSEIDON CYLKON 5000, SHERWOOD MAGNUM BLIZZARD, U.S. DIVERS CONSHELF SE-2 (same as PRO DIVER)]: Comparing the performance of the SHERWOOD MAGNUM BLIZZARD second stage to the U.S. DIVERS CONSHELF SE-2 (both of similar structural design)

would indicate the SHERWOOD MAGNUM BLIZZARD to be the superior of the two. The SHERWOOD teflon coated components and heat retention system were effective in preventing second stage malfunction under test conditions. The POSEIDON CYKLON 5000 second stage design (side mount inhalation/exhalation diaphragms, operation device linkage with ejector) was also considered effective.

b. Pneumatically balanced, demand poppet (SCUBAPRO MK X/G-250): The SCUBAPRO G-250 second stage did malfunction due to second stage icing. Its relative performance, being the only second stage in this category, is considered moderate. However, its balanced design was considered to have played an important role in preventing free flow, as first stage pressures rose from a preset value of 118 psig to as high as 176 psig during the immersion study.

c. Pilot/Servo (AGA DIVATOR MK II Breathing Valve with AGA Mouthpiece, POSEIDON ODIN, POSEIDON THOR, SEA SPORT ZEPHER ZR-01, TEKNA 2100BX): The SEA SPORT ZEPHER ZR-01 and TEKNA 2100BX second stages were both identified to have malfunctioned due to icing. The AGA MK II breathing valve, POSEIDON second stage in the POSEIDON ODIN and THOR (both identical second stages) could not be specifically identified as having failed due to icing during the immersion study. In any case these second stages clearly out performed the SEA SPORT ZEPHER and TEKNA and are considered to be effective.

6. Total performance rating in cold water. Based on performance during cold water function evaluations the 10 open circuit SCUBA regulators are grouped in the following performance categories (present in alpha-numerical sequence):

a. Superior Performance:

AGA DIVATOR MK II Breathing Valve with AGA Mouthpiece/U.S. DIVERS ROYAL SL First Stage

POSEIDON CYKLON 5000

POSEIDON ODIN

POSEIDON THOR

SHERWOOD MAGNUM BLIZZARD

b. Moderate Performance:

SCUBAPRO MK X/G-250

c. Unacceptable:

SEA SPORT ZEPHER ZR-01

TEKNA 2100 BX

U.S. DIVERS CONSHELF SE-2

U.S. DIVERS PRO DIVER

VI. CONCLUSIONS

A. U.S. DIVERS Cotton Backed Diaphragms. Results of studies conducted with the U.S. DIVERS CONSHELF XIV, first stage, clearly indicated that cotton backed diaphragms substantially enhanced the control of intermediate pressures after exposure to cold conditions.

B. Breathing Resistance/Work of Breathing. In all cases, breathing resistance and the work of breathing values, of regulators equipped with cold water conversion kits or silicon grease, increased as a direct result of the modifications. Although total effects varied, all units evaluated were considered to be functionally safe at all depths up to 198 FSW.

C. Cold Water Function. Ten regulators were evaluated under laboratory conditions and grouped into three distinct performance categories. The results indicated a strong interdependence between first and second stages performance. In instances where first stage intermediate pressures rose excessively high immediately after freezing or during the immersion exposure, the use of pneumatically balanced second stages prevented total system failure.

During immersion studies, diaphragm first stage regulators provided greater consistency of control on overbottom pressures in comparison to piston regulators that use environmental silicon grease. Additionally, diaphragm units recorded no external freezes while silicon injected units did. Piston regulators required continuous checks and maintenance for extrusion of grease while diaphragm units suffered no extrusions. Materials used in the manufacture of main first stage diaphragms should be specifically selected to provide maximum flexibility and minimum rigidity during exposure to cold.

Second stage regulators of a conventional design (U.S. DIVERS and SCUBAPRO), exempting SHERWOOD, were consistently out performed by regulators of unconventional design (AGA, POSEIDON) that utilized balanced pilot/servo assist mechanisms. These units also incorporated features that lessened the effects of moisture and cold via the use of plastics, rubber valve sleeves, check valves, reduced area of exposed mechanical linkage, and removal of primary second stage actuation devices from the immediate and direct path of exhaled gases and splash back (moisture residue) from exhaust valves.

Overall, five regulators were considered superior performers, one considered moderate, and four unacceptable. It is emphasized that regardless of a regulators superior performance, proper standard operating procedures for cold water operations should always be followed.