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# Mechanical behaviour of laboratory made freeze-bonds as a function of submersion time, initial ice temperature and sample size

**Knut V. Høyland and Anders Møllegaard**
*Sustainable Arctic Marine and Coastal Technology (SAMCoT), Centre for Research-based Innovation (CRI), Norwegian University of Science and Technology, Trondheim, Norway and The University Centre on Svalbard (UNIS)*
*knut.Høyland@ntnu.no*

## Abstract

Two types of freeze-bonds were made in the UNIS cold laboratory. Pieces of ice were put together, submerged and tested. The dependency of their mechanical behaviour on the submersion time, initial ice temperature and sample size was investigated. The first set of experiments used big blocks and aimed at determining the spatial freeze-bond capacity and its variation within the block. The second set of experiments used cylindrical samples that were cut in the middle at 45°. In the big blocks experiment, the freeze bonds were stronger in the corners and on the sides than in the middle part of the block, and all samples failed along the freeze-bonds. This indicates that brine was pulled out from the sides and not pushed out by a freezing process. The freeze-bond capacity of the cylindrical samples firstly decreased with increasing submersion time and then stabilized. The initial temperature of the ice had a strong effect on the freeze bond capacity for short submersion times but less effect for long submersion times. The freeze bonds formed in 8 ppt water were stronger than those formed in 35 ppt water. The peak stress occurred when the freeze-bond temperature and salinity were both minimum, and supports the theory about freeze-bond brine volume determining the freeze-bond capacity in saline ice.

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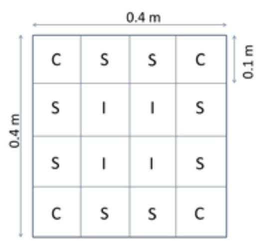
## 1. Introduction

Ice ridges are formed by shear or compression in the ice cover and give the design ice action for many Arctic offshore and coastal structures. One often (ISO, 2010) decomposes the forces from the consolidated layer and from the rubble (=unconsolidated layer). It is not clear how the micro-structure of the ice rubble affect/govern its mechanical behaviour, but it is reasonable that the bonding between ice blocks or the ice skeleton is of importance. Freeze-bonds have been studied by several researchers Ettema and Schaefer (1986), Shafrova and Høyland (2008), Repetto et al. (2011), Repetto and Høyland (2011a), Lishman et al. (2011), Bailey et al. (2012), Helgøy et al. (2013a and b), Schulson and Fortt (2013). A review was made by Repetto and Høyland (2011b) in 2011, and it turns out that its capacity is a function of a number of parameters: confinement, initial ice temperature, the salinity of the ice and the water, the submersion time, or holding time in air, the ice texture, the air volume and permeability of the ice, the samples size and geometry, and perhaps the loading rate. In a dimensional framework the mechanical properties of the freeze-bond are a function of size, temperature and time. In the present paper we will present measurements on how bond strength depends on the sample size, the submersion time and the initial ice temperature. A full description of this work can be found in Møllegaard (2012).

## 2. Experimental set-up

2.1 Big blocks experiment

A 0.1 m thick ice cover was created in FRYSIS in the UNIS laboratory from water with a salinity of 8 ppt. FRYSIS is a 1.2 m high tank measuring 0.5 m times 1 m in the horizontal plane. The side walls and the bottom plate can be heated so that the ice grows from the top. Two blocks with dimensions 0.4 m x 0.4 m were cut out and stored for 24 h in -15°C. Then the blocks were put on top of each other with the two top surfaces facing each other, and submerged 0.2 m below the surface in FRYSIS for 23 h. A 4 x 4 grid was made and 16 samples were cut with dimensions of 0.1 m x 0.1 m x 0.2 m, giving 4 corner samples, 8 side samples and 4 internal samples (C, S and I in Fig. 1 a). Table 1 gives the main input variable and the samples were tested in direct shear as shown in Fig.1.

a) 

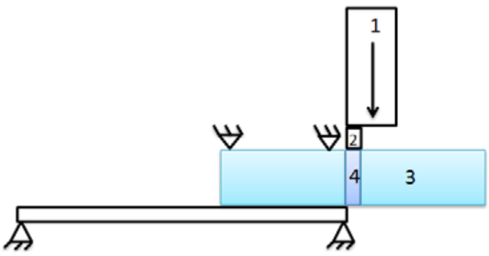

b) 


**Figure 1**. The big block experiments a) Sampling of Corner, Sides and Internal samples, b) The direct shear tests, 1 is the piston, 2 a wooden piece, 3 one of the original blocks and 4 the freeze-bond.

2.2 FIXIS experiments

A 30 cm thick ice cover was grown in FRYSIS. Thirty to forty cylindrical cores with diameter of 70 mm were sampled and stored in plastic bags to reach the desired initial ice temperature (see Table 2). The final samples were 175 mm long. The cores were then cut with a 45° angle, mounted in FIXIS (Fig. 2 a) and submerged to allow freeze-bonds to form. After being submerged (Fig. 2 b)) the samples were tested in constant speed uni-axial compression in

KNEKKIS, force-time recorded and pictures were taken. The freeze-bond salinity was measured by sampling after testing and on parallel samples. The porosity was calculated as given by Cox and Weeks (1983) for cold ice and Leppäranta and Manninen (1982).

**Table 1**. Parameters in the big-blocks experiment, the submersion time (Δt), the water and ice block salinities ($S_w$ and $S_i$), the temperatures of the ice before submersion ($T_{i,0}$), during testing ($T_{test}$) and in the water ($T_w$).

| $\Delta t$ (min) | $S_w$ (ppt) | $S_i$ (ppt) | $T_{i,0}$ (°C) | $T_{test}$ (°C) | $T_w$ (°C) | Surface smoothness |
|---|---|---|---|---|---|---|
| 1380 | 9.5 | 2.9 | -16.8 | -2.0 | -0.5 | Smooth |

**Table 2**. Number of experiments with FIXIS for sea water salinity of 8 ppt.

| | | $\Delta t$ (min) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0.5 | 1 | 5 | 20 | 60 | 1200 |
| $T_{i,0}$ | ≈-2.5°C | 0 | 0 | 4 | 3 | 3 | 3 |
| | ≈-8.5°C | 4 | 6 | 6 | 4 | 4 | 4 |
| | ≈-15°C | 0 | 4 | 5 | 3 | 3 | 2 |

**Figure 2**. a) Sample about to be assembled in FIXIS, b) Sample right after the submersion in FIXIS.

## 3. Results

### 3.1 Big block experiment

The peak shear stress ($\tau_{peak}$) was calculated by dividing the peak force by the nominal freeze-bond area (0.1 m x 0.1 m), and as Table 3 shows the more exposed the freeze-bond had been to the surrounding sea water, the stronger they became.

**Table 3**. Mean and standard deviation of the peak shear stress ($\tau_{peak}$), the number of tests and the failure location in the big-block experiment.

| | Corners | Sides | Internal |
|---|---|---|---|
| Mean (kPa) | 165 | 108 | 37 |
| Standard deviation (kPa) | 87 | 35 | 16 |
| Number of tests (-) | 4 | 8 | 4 |
| Failure location | Freeze-bond | Freeze-bond | Freeze-bond |

3.2 FIXIS experiments

Also here we defined an average shear stress across the freeze-bond area at failure as $\tau_{peak}$. The failure mode and $\tau_{peak}$ depended on both the submersion time ($\Delta t$) and the initial ice temperature ($T_{i,0}$) (Fig.3 and Table 4). The submersion time affected the two series with cold ice ($T_{i,0}$ =-8.5°C and -15°C), whereas it hardly affected the initially warmer ice ($T_{i,0}$ =-2.5°C). The initial ice temperature was important for short submersion times (less than approximately 1 hour), and the intermediate (but still cold) $T_{i,0}$ of -8.5°C gave the strongest samples.

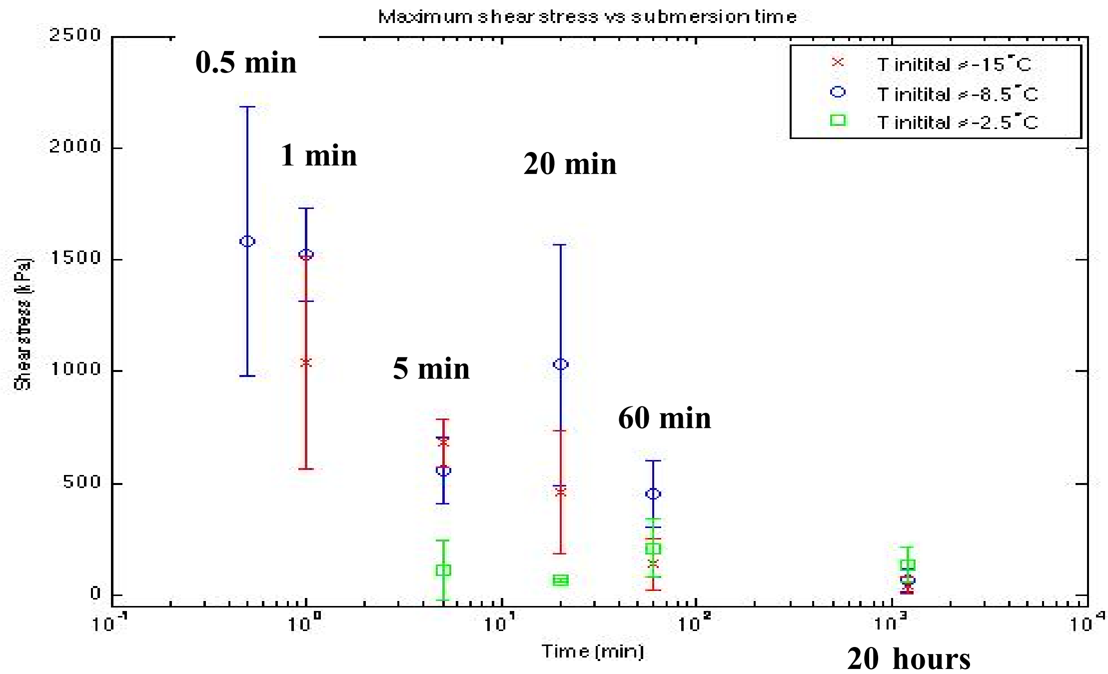



**Figure 3**. Peak shear stress ($\tau_{peak}$) vs. submersion time ($\Delta t$) for the three initial temperatures ($T_{i,0}$) of -15°C, -8.5°C and -2.5°C and the six submersion times $\Delta t$ = 0.5, 1, 5, 20, 60 and 1200 minutes.

**Table 4** Results from FIXIS experiments, Mean (standard deviation) of the peak shear stress (kPa) and the failure modes.

| | | $\Delta t$ (min) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0.5 | 1 | 5 | 20 | 60 | 1200 |
| | ≈-2.5°C | - | - | 110 (33) | 63 (5.7) | 208(1319) | 132 (78) |
| | | - | - | FB failure | FB failure | FB failure | FB failure |
| $T_{i,0}$ | ≈-8.5°C | 1583 (604) | 1419 (213) | 617 (151) | 1152 (532) | 474 (129) | 66 (54) |
| | | Block split | Block split | ? | FB failure | FB failure | FB failure |
| | ≈-15°C | - | 1038 (478) | 680 (107) | 460 (278) | 138 (116) | 42 (39) |
| | | - | Block split | Block split | FB failure | FB failure | FB failure |

**4. Discussion**

4.1 Big block experiments

We believe that the freeze-bond strength is mostly governed by its brine fraction. During the formation the trapped water is already at its freezing point ($T_f$) so that when ice starts forming in the freeze-bond the brine salinity goes up and $T_f$ decreases. This means that the essential mechanism for further ice creation is the removal of salt. Salt can either drain along the freeze-bond or into the original ice blocks. If the original ice is drained, that is it has empty inter-connected brine channels, the salt from the freeze-bond can relatively quickly be transported into the ice blocks allowing for more freezing, lower porosity and stronger freeze-bond (such as the ice-foot ice in the experiments of Shafrova and Høyland, 2008). If on the other hand the original ice is un-drained, the salt has to move along the freeze-bond and in this case the physical size of the freeze-bond area becomes important. Høyland and Shafrova (2003, unpublished results) carried out a freezing experiments with un-drained saline ice and similar dimensions as we used, and found that the two blocks were frozen around the edges, but not in the centre. They also found higher freeze-bond salinity further away from the edge. We suggest that our measured horizontal spatial variation in strength (Table 3) is due to similar variations in the freeze-bond brine volume and that the brine was pulled out from the surrounding water.

4.2 FIXIS experiments

Our dependence on submersion time ($\tau_{peak}$ - $\Delta t$) is similar to what Repetto et al. (2011) found in their direct shear testing of 3 times larger freeze-bond areas (even though we did not capture the increasing trend). Figure 4 shows a sketch of the measured temporal development of some different parameters (see Appendix for numerical values). It supports the theory of Repetto and Høyland (2011a) that the porosity (relative air and brine volumes) of the freeze-bond ($\eta_{fb}$) governs its mechanical properties and that the development can be described in three stages. In the first stage the freeze-bond is warmer than the ice and cools down so that $\eta_{fb}$ decreases. The bonds get stronger and may even become stronger than the original ice so that the freeze-bond sample fails by splitting (Table 4). When $T_{fb}=T_i$ the cooling (and freezing) stops and the ice is heated. The freeze-bond salinity reaches its minimum and starts to increase. Now we enter the second stage and $\eta_{fb}$ increases so that the bonds become weaker until the ice and water temperatures become equal and stage three begins. At this point the salinities of the ice and the freeze-bonds have also become fairly close. As there are only small (or none) gradients in temperature and salinity both $\eta_{fb}$ and the mechanical properties change slowly or little.

The initial ice temperature was important for submersion times less than 1 hour. The freeze-bonds were strongest for the -8.5°C and we suggest (as did Repetto and Høyland, 2011a) that the colder ice (-15°C) made the freeze-bond form so fast that more brine was locked in and that $\eta_{fb}$ became higher making the freeze-bonds weaker. When the ice was warmer less cold was available to freeze ice so that once again $\eta_{fb}$ became higher than for $T_{i,0}$=-8.5°C and freeze-bonds weaker.

Not only the shape of the $\tau_{peak}$ - $\Delta t$ curve was similar to that of Repetto and Høyland (2011a), the time scales were almost equal in spite of different experimental set-ups and that our freeze-bond area was about 1/3. But our average values ranged from 42 to 1583 kPa, while Repetto and Høyland (2011a) measured 5 to 20 kPa. Shafrova and Høyland (2008) used a similar test set-up as we did and submerged their samples for 20 hours and measured values of approximately 10 - 20 kPa for saline ice, somewhat less than we did. Repetto and Høyland (2011b) show that a failure model with a cohesion of 4.5 kPa and a friction angle of 30° may fit both their results and those of Shafrova and Høyland (2008). Shafrova and Høyland (2008) only tested for submersion

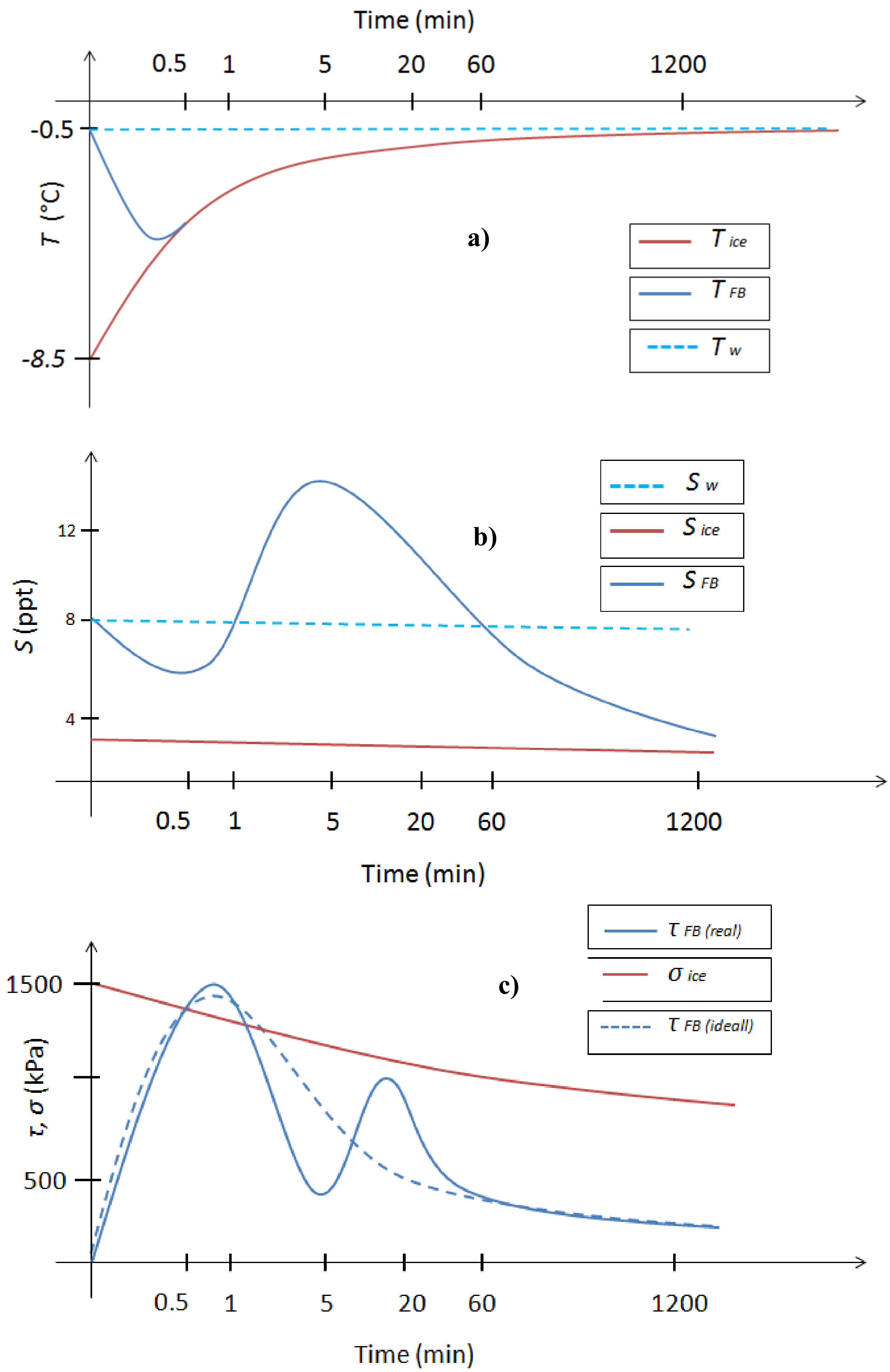



Figure 4. a) The ice temperature, b) the salinities and c) the peak stress in freeze-bond ($\tau_{peak}$) vs. submersion time $\Delta t$ for $T_{i,0}$ =-8.5°C.

times of 24 hours and more, so we have no other experiments to compare our short submersion time with. In some experiments (ours and those of Shafrova and Høyland, 2008) the shear and normal stresses on the freeze-bond plane were always equal so that we tested the freeze-bond with proportional loading, in most other experiments the normal stress was applied first and then the shear stress. In the first case the failure can occur for much higher shear stress for the same material properties.

## 5. Conclusions

Two types of experiments were carried out in the UNIS cold laboratory. In the first two big block (0.4 m square with 0.1 m thickness) were put together and submerged to allow a freeze-bond to form. In the second smaller cylindrical samples (70 mm diameter and 175 mm length) were cut 45°, put together and submerged. The samples were then tested mechanically. The experiments support the theory that the brine volume in the freeze-bonds governs its mechanical properties.

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# 6. Appendix

Table A1. Principal parameters used in experiments. Submersion time (*Δt*), salinity water bucket ($S_w$), salinity of the ice after testing ($S_i$), salinity freeze-bond ($S_{fb}$), ice temperature before submersion ($T_i$), temperature of the water in the bucket ($T_w$), temperature of the ice during testing ($T_{test}$), surface roughness (*SR*), failure along the freeze-bond plane or not, freeze-bond shear stress. All tests were done with a loading rate of 0.8 mm/min.

| *Test nr.* | *Δt (min)* | $S_w$ *(ppt)* | $S_i$ (ppt) | $S_{fb}$ *(ppt)* | $T_i$ *(°C)* | $T_{air}$ *(°C)* | $T_w$ (°C) | $T_{test}$ *(°C)* | *Surface Roughness* | FB failure | $\tau_{peak}$ *(kPa)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ***Series 1*** | | | | | |
| 1 | 0.5 | 8.0 | 3.0 | - | -8.7 | ~7.5 | -0.5 | -5.2 | ROUGH | N | 864 |
| **2** | 0.5 | 8.0 | 3.3 | 6.5 | -8.6 | ~7.5 | -0.5 | -4.8 | “ | N | 2104 |
| 3 | 0.5 | 8.0 | 3.0 | - | -8.6 | ~7.5 | -0.5 | -4.6 | “ | N | 2061 |
| 4 | 0.5 | 8.0 | 5.8 | - | -8.7 | ~7.5 | -0.5 | - | “ | N | 1302 |
| 5 | 1 | 8.2 | 3.0 | - | -8.4 | ~7.5 | -0.4 | - | “ | N | 1647 |
| 6 | 1 | 8.2 | 1.7 | - | -9.0 | ~7.5 | -0.5 | - | “ | N | 1635 |
| 7 | 1 | 8.2 | 3.0 | - | -8.8 | ~7.5 | -0.5 | - | “ | N | 1283 |
| 8 | 5 | 8.8 | 2.9 | 12.4 | -8.5 | ~7.5 | -0.5 | -3.5 | “ | ? | 702 |
| 9 | 5 | 8.8 | 3.1 | - | -7.5 | ~7.5 | -0.5 | -3.6 | “ | ? | 559 |
| 10 | 5 | 8.8 | 3.2 | 14.8 | -9.1 | ~7.5 | -0.5 | -4.2 | “ | ? | 406 |
| 11 | 20 | 8.2 | 3.0 | - | -8.9 | ~7.5 | -0.4 | - | “ | Y | 969 |
| 12 | 20 | 8.2 | 2.9 | 8.2 | -8.4 | ~7.5 | -0.4 | - | “ | Y | 1925 |
| 13 | 20 | 8.2 | 3.8 | - | -9.1 | ~7.5 | -0.5 | - | “ | Y | 708 |
| 14 | 20 | 8.2 | 3.2 | 10.6 | -8.7 | ~7.5 | -0.5 | -2.2 | “ | Y | 1004 |
| 15 | 60 | 8.2 | 3.2 | - | -8.8 | ~7.5 | -0.5 | -1.6 | “ | Y | 293 |
| 16 | 60 | 8.2 | 2.8 | 8.0 | -8.9 | ~7.5 | -0.5 | -1.6 | “ | Y | 478 |
| 17 | 60 | 8.2 | - | 6.4 | -8.8 | ~7.5 | -0.5 | -1.3 | “ | Y | 590 |
| 18 | 60 | 8.0 | 3.1 | - | -8.6 | ~7.5 | -0.5 | -1.3 | “ | Y | 535 |
| 19 | 1200 | 8.7 | - | - | -8.2 | ~7.5 | -0.5 | -0.6 | “ | Y | 47 |
| 20 | 1200 | 8.7 | - | 4.0 | -8.8 | ~7.5 | -0.5 | -0.6 | “ | Y | 77 |
| 21 | 1200 | 8.0 | 4.1 | 3.8 | -8.5 | ~7.5 | -0.5 | -0.6 | “ | Y | 6 |
| 22 | 1200 | 8.0 | 3.5 | 4.0 | -8.0 | ~7.5 | -0.5 | -0.7 | “ | Y | 135 |
| | | | | | | **Series 2** | | | | | |
| 24 | 5 | 7.9 | - | - | -8.0 | ~7.5 | -0.5 | -3.3 | “ | - | 535 |
| 25 | 5 | 7.9 | - | - | -8,3 | ~7.5 | -0.5 | -3.3 | “ | - | 657 |
| 26 | 5 | 7.9 | - | - | -8.3 | ~7.5 | -0.5 | -3.5 | “ | - | 843 |
| 27 | 1 | 7.9 | - | - | -8.3 | ~7.5 | -0.5 | -4.3 | “ | N | 1356 |
| 28 | 1 | 7.9 | - | - | -8.1 | ~7.5 | -0.5 | -4.7 | “ | N | 1174 |
| | | | | | | **Series 3** | | | | | |
| 29 | 1 | 8.0 | 3.3 | - | -14.6 | -14.7 | -0.5 | -6.7 | “ | N | 390 |
| 29-2 | 1 | 8.0 | 2.8 | - | -15.4 | -15.4 | -0.5 | -6.7 | “ | N | 977 |
| 29-3 | 1 | 8.0 | 2.8 | - | -14.8 | -15.2 | -0.5 | “ | “ | N | 1319 |
| 31 | 1 | 8.0 | 2.0 | - | -14.9 | -15.3 | -0.5 | “ | “ | N | 1465 |
| 32 | 5 | 8.2 | 2.9 | - | -14.9 | -15.4 | -0.5 | -3.5 | “ | N | 561 |
| 33 | 5 | 8.2 | 2.6 | - | -15.2 | -15.2 | -0.5 | “ | “ | N | 713 |
| 34 | 5 | 8.2 | 3.1 | - | -15.2 | -15.5 | -0.5 | “ | “ | N | 767 |
| 35 | 20 | 8.0 | 3.1 | - | -15.4 | -15.0 | -0.5 | -2.1 | “ | Y | 770 |
| 36 | 20 | 8.0 | 3.3 | - | -15.4 | -14.5 | -0.5 | “ | “ | Y | 235 |
| 37 | 20 | 8.0 | 3.3 | - | -15.1 | -14.4 | -0.5 | “ | “ | Y | 374 |
| 38 | 60 | 8.0 | 2.0 | - | -14.5 | -15.0 | -0.5 | “ | “ | Y | 19 |
| 39 | 60 | 8.0 | 2.7 | - | -14.8 | -15.4 | -0.5 | -1.2 | “ | Y | 251 |
| 40 | 60 | 8.0 | 2.5 | - | -14.6 | -14.9 | -0.5 | -1.4 | “ | Y | 144 |
| 41 | 1200 | 8.1/13.3(*) | - | - | -15.6 | -15.1 | -0.5 | -0.7 | “ | Y | 14 |
| 42 | 1200 | 8.1/13.3(*) | - | - | -15.6 | -15.1 | -0.5 | -0.7 | “ | Y | 69 |
| | | | | | | **Series 4** | | | | | |
| 43 | 5 | 8.0 | 2.5 | 10.3 | -2.4 | -1.3 | -0.5 | -2.1 | “ | Y | 308 |
| 44 | 5 | 8.0 | 2.3 | 10.0 | -2.4 | -1.0 | -0.5 | -1.9 | “ | Y | 28 |
| 45 | 5 | 8.0 | 1.9 | 10.3 | -2.3 | -2.1 | -0.5 | - | “ | Y | 58 |
| 45-2 | 5 | 8.0 | 2.7 | 10.9 | -2.1 | -1.1 | -0.5 | -2.1 | “ | Y | 45 |
| 46 | 20 | 8.0 | 2.3 | 9.1 | -2.7 | -2.5 | -0.5 | -1.7 | “ | Y | 69 |
| 47 | 20 | 8.0 | 2.6 | 11.7 | -2.6 | -2.5 | -0.5 | -1.8 | “ | Y | 58 |
| 48 | 20 | 8.0 | 2.2 | 8.8 | -2.6 | -2.0 | -0.5 | -1.6 | “ | Y | 61 |
| 49 | 60 | 8.0 | 0.8 | 6.1 | -2.9 | -3.2 | -0.5 | -1.3 | “ | Y | 298 |
| 50 | 60 | 8.0 | 1.8 | 7.2 | -3.4 | -3.9 | -0.5 | -1.3 | “ | Y | 58 |
| 51 | 60 | 8.0 | 2.9 | 8.0 | -3.0 | -2.9 | -0.5 | -1.3 | “ | Y | 269 |
| 51-3 | 1200 | 8.0 | - | - | -2.7 | -1.1 | -0.5 | -0.7 | “ | N | 222 |
| 51-4 | 1200 | 8.2 | - | - | -2.7 | -2.1 | -0.5 | -0.6 | “ | Y | 81 |
| 51-5 | 1200 | 8.2 | - | - | -2.7 | -2.1 | -0.5 | -0.6 | “ | Y | 94 |
| | | | | | | **Series 5** | | | | | |
| 52 | 20 | 34.0 | - | - | -8.7 | -9.4 | -1.9 | -3.2 | “ | “ | - |
| 53 | 20 | 34.0 | - | - | -8.6 | -8.5 | -1.9 | - | “ | “ | |
| 54 | 60 | 34.0 | - | - | -8.6 | -9.4 | -1.9 | - | “ | - | - |