Center for Independent Experts (CIE) Review of the Bering Sea Snow Crab Stock Assessment

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February 2014

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1. Executive Summary

1. A review of the length-based assessment and projection models for the eastern Bering Sea population of the snow crab *Chionoecetes opilio* was undertaken in Seattle by a CIE Review Panel between 21 and 24 January 2014.
2. The long time series of NMFS trawl survey data and ADFG observer data that are available for analysis are major strengths of the assessment model.
3. Further research studies need to be undertaken to address the current paucity of data for natural mortality. Use of the zones within the eye stalks of snow crabs offers considerable promise for ageing, but tagging studies could provide valuable additional data on mortality.
4. Growth of immature crabs should be described in the model using a segmented linear rather than linear relationship.
5. The collection of additional pre- and post-molt data from immature snow crabs is essential as a sound description of growth is a prerequisite if assessment and projection model outputs are to be reliable.
6. Further research should be undertaken to improve understanding of the migrations and varying spatial distributions of the primiparous and multiparous females and the mature males, and the relative contributions of the primiparous and multiparous females to the reproductive potential of the stock. In particular, the relationship between mature male biomass (MMB) at the time of mating and the reproductive potential of the female crabs requires investigation.
7. Current descriptions require refinement such that they describe the assessment and projection models with greater clarity and provide mathematical descriptions that are complete and accurate. The ways in which the input data were collected and processed prior to input to the model need to be described in greater detail.
8. It appeared from the (rather inadequate) description of the model within the Assessment Report, and the advice provided by Dr Turnock at the Review Meeting, that the conceptual model for the dynamics of the EBS snow crab population is sound.
9. Other than aspects relating to the terminal molt and the male-only nature of the fishery, the underlying structure of the assessment model is similar to that successfully used in a number of other length-based models.
10. It is recommended that the starting year considered in the model should be changed from 1978 to 1982, thereby removing the survey data from 1978 to 1981, a period in which the survey net differed from that used in subsequent years.
11. The assumption used when analysing the results of the BSFRF-NMFS comparative trawling studies that the *Nephrops* trawl net caught all snow crabs in the area that it swept is likely to be erroneous. Sensitivity of model results to this assumption and to excluding these data from the assessment should be investigated.
12. Other recommendations are included in the discussions addressing the various terms of reference.

2. Background

2.1. Overview

Since its last review by the CIE in 2008, numerous improvements had been made to the assessment model for the Bering Sea snow crab *Chionoecetes opilio* to incorporate new data on selectivity, growth, and discard mortality. As the modified model represented a substantial change to the earlier model, it was considered necessary by the Alaska Fisheries Science Center that the revised model should be subjected to review by an independent panel. Broadly, such a review would encompass the survey and life history data for the Bering Sea snow crab, the structure and assumptions of the new assessment model structure, and the harvest control rule.

A panel comprising three independent reviewers was contracted by the Center for Independent Experts (CIE) to undertake an independent peer review of the new assessment model and the data that formed the input to that model. The panel selected by the CIE to undertake this review comprised Drs Billy Ernst, Noel Cadigan, and Norm Hall.

On January 7, 2014, the reviewers received a copy of the assessment report and relevant background documents that were the subject of the review. A list of these documents is presented in Appendix 1. Additional documents providing explanatory information, but which were not part of the material to be reviewed, were made available to the members of the Review Panel during the course of the review. These have been included in the list of references when they have been cited in this report.

The Statement of Work provided to Dr Norm Hall by the CIE is attached as Appendix 2. This report documents the findings of the independent review that was undertaken by Dr Hall in accordance with this CIE Statement of Work.

2.2. Terms of Reference

The terms of reference for this independent peer review of the stock assessment for the Bering Sea snow crab are presented in Annex 2 of Appendix 2.

2.3. Date and place

The review of the Bering Sea snow crab stock assessment was conducted at a meeting chaired by Dr Martin Dorn at the Alaska Fisheries Science Center (AFSC) in Seattle, Washington, between 21 and 24 January 2014. Among those who attended the meeting were Drs Jack Turnock, William Stockhausen, Dan Nichol, Athol Whitten (on 21 and 22 Jan), and Cody Szuwalski (on 22 Jan), while Dr Bob Foy provided a telephone/video presentation on the aspects of the Bering Sea surveys pertaining to snow crabs from his office in Kodiak.

2.4 Acknowledgments

Thanks are expressed to the various individuals who participated in the review meeting, and who contributed to the stock assessments and discussions, for making the review such an interesting experience. The presenters are to be commended for the quality of their research and presentations, and for their very competent and professional responses to the Panel's queries and requests. Thanks are also extended to the Chairman, Dr M. Dorn (NMFS) for his assistance in providing access to review materials and background information, and for ensuring the smooth running of the review meeting. The valuable insights, comments, and recommendations offered during the review meeting by Drs N. Cadigan and B. Ernst are gratefully acknowledged.

3. Description of Reviewer's role in review activities

As required under the CIE's statement of work, the reviewer familiarised himself with the documents that had been provided and then, together with other review panel members, undertook the review that had been requested, addressing each of the terms of reference specified in the statement of work.

Note that, at the outset of the review panel meeting, the panel was advised by the Chair that the focus of the review was the quality of the stock assessment and the input to that assessment, and that, although the project description in the statement of work advised that the review encompassed the harvest control rule, the terms of reference did not include this. The panel was instructed to disregard this element of the project description, and not to focus on projections or reference points as review of the harvest control rule for snow crabs would require consideration of the implications for other crab fisheries in the region. The panel was also advised that it was not required to identify a preferred model structure, nor to produce a combined report of the review panel meeting.

1. Summary of findings

ToR 1. Statement of the strengths and weaknesses of the Bering Sea snow crab stock assessment and stock projection models.

The Bering Sea snow crab assessment and projection model provides a representation of the population of snow crab *Chionoecetes opilio* that occupies the coastal shelf of the eastern Bering Sea (EBS) and the fishery that exploits that population.

In broad terms, the life history of these crabs is as follows. The crabs hatch in spring, with hatching starting in March and ending in June but with most hatching occurring in April and May (Fig. 1) (Ernst et al., 2005; Parada et al., 2010). By the time the immature individuals have grown to the size range represented in the model, i.e. 25 to 135 mm carapace width, and until they undergo a terminal molt to become morphometrically-mature, these crabs are assumed to molt once per year in the spring, i.e. March-April (Turnock and Rugolo, 2013 Assessment Report). The snow crabs that have undergone a terminal molt can be distinguished from morphometrically-immature individuals. Those that have only recently undergone this molt can be distinguished by their clean shell, which contrasts with the shell condition of those crabs that underwent their terminal molt a number of years earlier. The molt to maturity that females experience occurs in February-March, following which these primiparous females mate (Parada et al., 2010). Following hatching, multiparous females may mate (Parada et al., 2010). Thus, mating occurs in late winter or early spring following which egg extrusion and fertilization occurs. While hatching typically occurs one year afterwards, ovigerous females inhabiting waters at or below 1° C enter diapause and retain eggs for two years before hatching. The model, however, assumes an annual reproductive cycle. The relative contribution of primiparous and multiparous females to total reproductive potential is unknown.

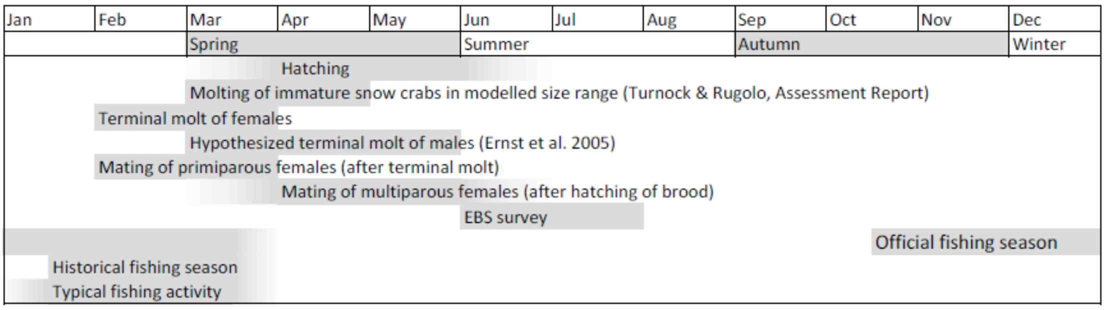

Figure 1. Schematic representation of key stages and events in the eastern Bering Sea snow crab fishery.

The National Marine Fisheries Service (NMFS) undertakes an annual summer trawl survey (typically) in June and July (Fig. 1), at which time details of clutch fullness of ovigerous females are recorded, together with details of catches and characteristics of sampled snow crabs such as size, sex, maturity status, shell condition, etc.

A directed pot fishery exploits the male snow crabs during winter months (Fig. 1). Historically the snow crab fishery started on January 15. In recent years, the official snow crab fishing season has opened in mid-October and closed in mid to late May, with a region around the Pribilof Islands closed to fishing in order to protect the blue king crab stock. Although now officially allowed to start in October, fishing still tends to commence in January. The fishery does not operate over the entire area covered by the annual EBS trawl survey as it is constrained to the southern portion of this region by ice cover, the extent of which varies inter-annually. The legal minimum carapace width of 78 mm for snow crabs represents the width at which 50% of males are likely to be mature, but fishers typically select and retain crabs that have shell widths > 101 mm. A mandatory observer programme, which is operated by the Alaska Department of Fish and Game (ADFG), collects data on catch per sampled pot, and records characteristics of the crabs in the sampled pots such as the number of crabs that were expected to be retained or discarded, and the size, sex, and shell condition of the crabs within each of those two categories. Fishers record details of catches and pot lifts in daily fishing logs (DFLs).

Because of its economic importance, the population and biological characteristics, distribution and movements of snow crab *Chionoecetes opilio* that occupy the coastal shelf of the EBS have been the subjects of numerous studies. Research studies on snow crabs in the EBS are hampered, however, by ice cover, particularly in winter months. Research has extended to studies to determine the efficiency of the survey gear used to produce estimates of abundance, data on size compositions, and samples of crabs for use in biological studies. Data on the snow crabs in the EBS have been supplemented by surveys and studies undertaken on the continental slope of the EBS and in the northern Bering Sea. Knowledge of the biology of the snow crab has been augmented by data gained from other populations of this species in the Chukchi and Beaufort Seas, and in the eastern Atlantic Ocean.

Assessment model

In common with other fishery assessment models, the assessment model for the EBS population of snow crabs uses data on removals (catches and deaths of discarded fish) and survey estimates of abundance to estimate trends in recruitment and abundance. These data are supplemented by the information contained in size and sex composition data, and data on the maturity status of crabs in samples collected from survey catches, and from catches and discards by fishers. The model makes use of estimates of natural mortality and growth, and data relating to reproduction, but, unlike fisheries for teleosts, is unable to use age composition data as such data are unavailable. As with many other stock assessments, despite the fact that movement of the crabs and their spatial distribution, and the spatial distribution of the fishery, are important aspects of the dynamics of the snow crab population, the model assumes a single area and does not attempt to model the spatial dynamics of the snow crabs. The current state of the population at a particular point in time is represented in the model by the numbers of morphometrically-immature, clean-shelled morphometrically-mature, and older-shelled morphometrically-mature snow crabs of each sex within each of a number of size bins. Whereas age-dependent models update the modelled state from year to year by updating the age of the individuals, the length-based model employs a size-transition matrix to update the size composition of the immature crabs and employs maturation curves to determine the numbers of crabs of each sex that undergo a terminal molt.

The principal differences between length- and age- structured models are the absence of age-composition data and reliance on a size-transition matrix to update the system state for the former type of model. The information on mortality contained in length-composition data is considerably less than that which is present in age-composition data, partly due to the fact that, as individuals become older, differences among mean sizes of individuals in successive year classes diminish, but also because variation in growth "smears" the length distribution of individuals of a particular year class over a number of size bins. For older individuals, this makes it difficult to discriminate and track the different year classes through successive sets of observed annual size composition data.

Apart from elements relating to the terminal molt and the male-only nature of the pot fishery, the structure of the length-based model of the EBS snow crab population is similar to that of a number of other length-based models that have been used successfully to assess the invertebrate stocks they represent.

Projection model

The structure of the projection model that was used to project the state of the EBS population of snow crabs forward over a number of years was the same as that used for the length-based assessment. Although not described in the Assessment Report, the Review Panel was advised by Dr Turnock that the estimates of annual recruitment from the fitted assessment model were averaged. The resulting mean recruitment was then held constant while, using a constant value of *F*, the model was projected forward over successive years until the population achieved equilibrium. The value of *F* was adjusted to determine F35%, the value that reduced MMB (at the time of mating) to 35% of its unfished level. As described in the Assessment report, these values of B35% and F35% were used to calculate the parameters R_0 and steepness h of a Beverton and Holt stock-recruitment model. This stock-recruitment model was then employed in the projections to generate successive values of auto-correlated annual recruitment. Finally, for these projections, the predicted state of the stock at the end of the time series of catch and survey data was updated through successive years using the randomly-selected values of recruitment and with specified values of annual *F*.

Model description

As noted earlier, the description of the model is unclear and lacks mathematical precision. Moreover, variables are often poorly described, e.g. there is no equation describing how the estimated value of survey biomass, $S\hat{B}_t$, is calculated. As another example, the equation that calculates the number of immature crabs within each length bin in the second and subsequent years of the modelled period assumes that an instantaneous rate of total mortality Z_l^s is applied throughout the year, yet fishing is assumed to be imposed as a pulse. That is, the description of the assessment model incorrectly mixes the concepts of continuous and pulse fishing and the equations become inconsistent. The model provides no equation for calculating the discards of females from the pot fishery, or separating the total male catch into the catch from the pot fishery and the discards from the trawl fishery. No equation is presented to link the removals of catch and those discarded crabs that are lost through discard mortality to the variable denoting the total mortality Z_l^s. The description of the projection model is also inadequate. There is no description in the Assessment Report of the methods used to calculate the estimates of B35% and F35%, nor is there a description of how the initial state at the beginning of the projection period was determined. As the Assessment Report advises that variability in recruitment was simulated in the projection model with temporal autocorrelation, it would be expected that the number of simulations used to generate the data reported in Tables 9 a and b of the Assessment Report would have been specified.

The Assessment Report advises that the parameters representing the fishing mortalities for males, discarded females and trawl discards were constrained such that the predicted catches closely matched the observed values. Only one equation relating catch to fishing mortality is presented, however, and that involves both the male and trawl fishing mortalities, not the female fishing mortality, which, although not explicitly stated, appears to be assumed to be equal to zero. In this case, it is not fishing mortality but the probability of capture that is of interest, and there may be an advantage if, rather than writing the equations in terms of fishing mortality, the equations are written in terms of probability of capture during the pulse fishery, as it is the crabs that are subsequently landed or die following discard that are removed from the population, not the total of what is caught. It is stated that the value for the fishing mortality of snow crabs for the trawl fishery is 0.01, yet no justification is presented for using this value as a prior. No equations are presented that define how the fishing mortality deviations for males, female bycatch and trawl bycatch are calculated, although penalty functions are defined for these deviations.

For model scenarios 3 and 4, likelihoods were applied to the intercept and slopes of the linear growth equations for males and females, based on the prior values of 6.773 for the intercept and 1.16 and 1.05, respectively, for the slopes. From the description provided in the Assessment Report, it appears that these likelihoods should not have been imposed for model scenarios 1 and 2, yet Table 13 of the Assessment Report records values for them.

It is recommended that the descriptions of both the assessment and projection models are re-written such that they are clear, complete, and mathematically consistent.

Initial state

The description of the assessment model would be improved by including a section describing how the initial state of the modelled population is determined. Although specified in the Assessment Report, the statement that "Seventy parameters were estimated for the initial population size composition of new and old shell males and females in 1978" lies buried in the middle of a paragraph and is not immediately apparent when reading the model description. It would also be useful to include in this section a comment relating to the smoothing constraint that was applied to these size-composition data.

Strengths and weaknesses

Particular strengths of the assessment and projection models include:

- The extensive time series of abundance and size-composition data from the annual EBS survey.
- The detailed time series of fishery data from the mandatory ADFG observer program.
- The data resulting from the numerous studies of the biology of snow crabs, both in the EBS and from other populations, and from the various studies of the efficiency of the trawl nets used in the annual NMFS survey.

Weaknesses of the models include:

- Stock structure is unknown. The modelled population of snow crabs, i.e. the crabs in the EBS survey area, does not encompass the full stock, e.g. the crabs in the northern Bering Sea and possibly those on the Russian side of the U.S.-Russian Convention line, and which thus would contribute to the reproductive potential of the population. The population in the EBS is not closed to migration from at least the northern Bering Sea, some of the individuals of which are believed to migrate into the EBS. The proportion of the full (genetic) stock that is represented by the population within the EBS is unknown and is likely to vary inter-annually.
- The data, on which estimates of mortality for females and for the mean of the prior of the mortality estimate for males were based, are limited, and the estimates of these input values are uncertain.

- Data on growth of immature males and females are limited, and, because of constraints on the area free of ice coverage from which the crabs that contributed growth data could be collected, are possibly unrepresentative of the growth of males and females in the full EBS population of snow crabs.
- The assessment and projection models are poorly described. Descriptions of both models, and the input data that are used, are inadequate. The descriptions should advise how the data were collected and analysed to produce the values that were input to the assessment model.

ToR 2. Recommendations for alternative model configurations or formulations.

Change of starting year of assessment to 1982

In response to concern that the estimate of Q for 1978-81 was 1.00 with an estimated SE of 0.00, and a request to explore the likelihood profiles of the component data sets for key parameters such as this, Dr Turnock produced the following output.

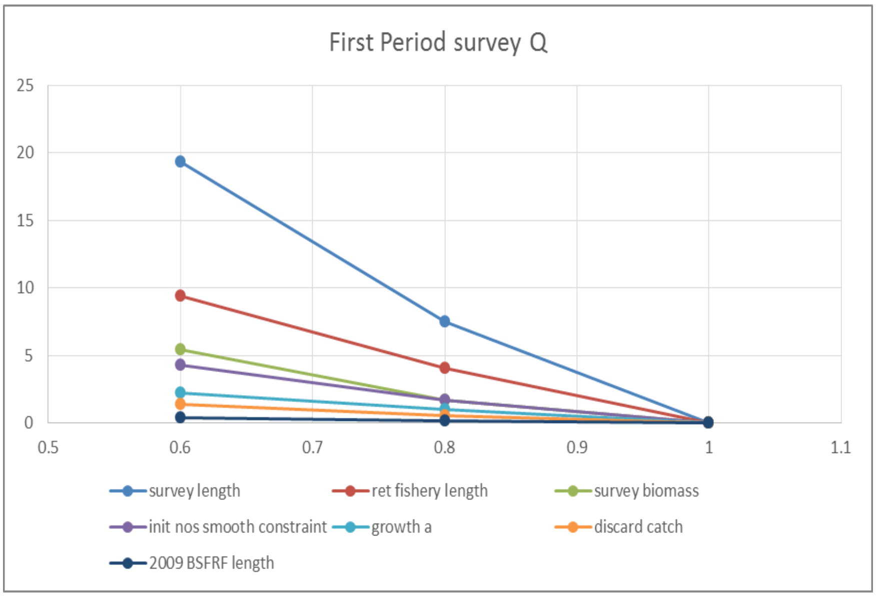

Figure 2. Profiles of the likelihoods of the components of the overall likelihood for the base model over a range of values for the estimate of Q for the period 1978 to 1981, where the likelihood of each component has been scaled by subtraction of the minimum value within that range. Note that the likelihoods of the different components are weighted (Table 11, Assessment Report).

Given the current model structure, all data sets appear consistent in their support for the value of Q = 1.00 that was estimated when fitting the model, yet the value to which the parameter estimate has converged represents the upper bound that was imposed when fitting the model. Further investigation of this issue would be warranted if it persists following modification of the growth model from a linear to a segmented linear model (see below). Rather than diverting attention to this issue from more profitable avenues of research to improve the assessment model, however, it is suggested that the data for 1978 to 1981 should be dropped, and the model modified to run from 1982 rather than 1978. This would ensure that the survey data that are used in the model have been collected in a consistent manner using the same type of trawl net, and thereby avoids any artefact introduced into the model by the use of a different survey trawl net between 1978 and 1981.

Form of growth curve

The panel noted that, for both females and males, the growth model used in the current base model provided a poor fit to the data from the 2011 growth study. Examination of a plot of the growth data suggested that they might be more appropriately modelled using a segmented straight line, such as that used by Somerton et al. (2013), rather than a linear equation, and it is recommended that the growth model be restructured accordingly. The Assessment Report noted, however, that difficulty in obtaining convergence was encountered when attempting to fit a segmented straight line to the molt-increment data for each sex. Because of this difficulty, linear equations had been used to describe the relationship between pre- and post-molt carapace widths.

It is possible that the difficulty in obtaining convergence when fitting the segmented line arose from the use of an "if test" in the ADMB code that was used to implement the assessment model, where such a test is likely to have been used when constructing the length transition matrix to determine which of the two line segments should be used to calculate the size of the expected molt increment. An approach that would avoid the use of an "if test" is to set the value of the pre-molt carapace width at the break point to a value that corresponds to the boundary between two size bins. Molt increments for all size bins less than carapace width at the break point would then be calculated using the first line segment, while the second line segment would be used for all size bins larger than the carapace width at the break point. Although this approach would not allow estimation of the break point, which would need to be specified prior to fitting the model, models employing different values of the break point could be fitted and the resulting log-likelihoods compared. It was suggested in the Review Meeting that the break point between the two line segments possibly marked the development of the gonads, i.e. physiological maturity, and that this might be expected to occur at ~40 mm.

Representativeness of growth data

The assessment model uses the data for individuals of each sex to estimate the parameters of the growth curve for that sex. It should be noted that, because ice cover constrained the locations from which they were collected, these crabs are unlikely to represent a random sample from the EBS population. Thus, while the resulting growth curves should provide an accurate description of the molt increment data for the 35 crabs that were input to the model, they may provide a biased description of the expected growth of randomly-selected individuals from the population. A possible approach to accommodate this potential bias is to describe the growth of the females and males in the EBS population using growth curves of similar functional form to that of the growth models fitted to the molt-increment data that were input for the 35 individuals, and to employ the resulting parameter estimates (and associated SEs) for these latter curves in prior probability distributions for the parameters of the growth curves for the EBS population as a whole.

Relating shell condition to elapsed time after terminal molt

The assessment model currently calculates the number of crabs that are expected to have undergone a terminal molt and thus become of shell condition SC2, i.e. clean shell within 3 to 12 months post-molt, at the time of the pulse fishery. Following the fishing season, in spring and thus prior to the EBS survey, individuals that were in shell condition SC2 are re-classified as being of shell condition SC3, i.e. old shell, mature individuals, and are added to the numbers of crabs within this category. Because of the uncertainty associated with the duration of the old shell (SC3), very old shell (SC4), and very, very old shell (SC5) states, the model does not attempt to classify old shell crabs into these further shell-condition categories. Currently, the data on the proportions of crabs of each sex that are in these different shell condition categories, which are collected during the EBS survey or by the observers on board the fishing vessels, do not appear to be used. Rather than keeping track of the numbers of crabs in shell conditions SC2 and SC3, it would be a simple modification to the model to keep track of the number of crabs that are in their first, second, third, etc., year of life following the terminal molt. Such data could readily be transformed to the SC2 and SC3 categories that are currently used in the model, but could also be used with input data on shell condition in a post-hoc analysis, i.e. after fitting the assessment model, to estimate the parameters of logistic curves relating the probability of crabs being in shell condition SC3, SC4, and SC5 states to the years that had elapsed since the terminal molt. While not adding additional information to improve the model fit, the results of such analysis would provide rough estimates of the duration of each shell condition state (conditional on the parameter estimates and structure of the fitted model).

Within-fishing season depletion

The fishery has been modelled as a pulse fishery, occurring 0.62 years after the start of the survey year, i.e. July 1, noting that the annual survey is undertaken in June-July (Turnock and Rugolo, 2013 Assessment Report). This 0.62 year time interval would be consistent with a mid-point of the fishing season at about 12 February, a value that is reasonably consistent with the mid-October commencement and mid to late May termination of the season. As an alternative model formulation, consideration should be given to replacing the pulse fishery assumption by the assumption of constant instantaneous fully-selected fishing mortality over the fishing season and modelling this using the Baranov catch equation. While the resulting estimates of the overfishing limit OFL and mature male biomass MMB at mating are unlikely to be greatly affected, the accuracy of the estimate of instantaneous fishing mortality (or probability of capture) would possibly be improved and the model would more readily allow use of declining within-season weekly catch per unit of effort (CPUE) (as a consequence of depletion due to removals) to provide additional information on the abundance of the snow crab stock. Thus, for the core areas in which the pot fishery operated, the catch and effort data reported in the daily fishing logs (DFLs) for each year, in combination with the CPUE data collected by ADFG observers, could be explored to determine whether Leslie or DeLury depletion analyses could provide information on local abundance and exploitation.

Effective sample size of size composition data

When calculating the likelihoods, it was assumed that each of the annual size compositions has an effective sample size of 200. Dr Turnock advised that, had the sample size over the whole fishery been less than 200, the actual sample size would have been used. Consideration should be given to calculating effective sample size for each size distribution using a method such as one of those described by Francis (2011).

Observation models and likelihoods

Dr Cadigan advised that the likelihoods used in the model should be based on the data that were observed, rather than derived data. Thus, for example, the proportions of the catch that were retained or discarded were determined from the samples examined by observers, and should have been considered as such when calculating the likelihood, rather than basing the likelihood on estimates of the total retained and observed catches. Dr Cadigan also advised that, for each component, the log-likelihood should be written and calculated in full, with variances being estimated in the model, thereby converting the model into a statistical model. Thus variances of indices might be represented as the sum of the variance of the various observed values that were input plus an additional variance associated with deviations of the observed values from the values predicted by the model. It is recommended that weights on the resulting likelihoods should be set to 1 when fitting the assessment model and while estimating effective sample sizes for size composition data, but then varied and the model re-fitted to explore how the different data sets influence the estimated values of the different parameters and whether tension exists among the values of those estimates favoured by the various component data sets. Note that the weights currently applied to the likelihoods of the different components appear arbitrary. Thus, for example, the weights for the catches of males, discarded females, and trawl discards were presumably chosen such that, as advised in the Assessment Report, the predicted catches were constrained to closely match the observed values.

BDFRF data

The current approach used to analyse the data from the paired trawl study, which was conducted in 2010 by the Bering Sea Fishery Research Foundation (BSFRF) and NMFS, does not capitalise on the fact that the industry and NMFS vessels fished side by side. Dr Cadigan recommended that a mixed effects model should be used to compare the catches made in the paired tows and thereby estimate the selectivity of the 83-112 Eastern survey net relative to that of the *Nephrops* trawl (e.g. Fowler & Showell, 2009). He advised that a similar approach could possibly be used for the 2009 study by employing the survey grid cell as a factor.

Dr Cadigan also advised that experience in Canada suggests that the assumptions that the value of Q for the *Nephrops* trawl is equal to 1, and that selectivity for this net does not vary with length, may be invalid. Thus, towed by different vessels and captained by different skippers, the ratio of survey catches made by a *Nephrops* trawl to those of a Department of Fisheries and Oceans (DFO) trawler varied by factors that ranged from 17 to as much as 31. This suggests that it may not be possible to use the BSFRF study to obtain a reliable estimate of survey Q and survey selectivity.

ToR 3. Recommendations for alternative model assumptions and estimators.

Size distribution of recruits

It would be useful if a clear definition of recruitment was provided in the Assessment Report. It appears that this represents the crabs within the EBS population that molt into the size range considered by the model, i.e. 25 – 135 mm carapace width, together with the crabs that (possibly molt and) migrate from outside the EBS into the area covered by the standard EBS survey and have carapace widths of 25 mm or larger. All recruits were assumed to possess clean shell, and to be morphometrically immature. Their sex ratio was assumed to be 1:1.

The size distribution of the recruits to the modelled population could not be estimated, and thus was specified as a fixed and constant distribution that spread the crabs over a number of carapace width bins and represented a number of instars. No details of the basis for the current recruitment size distribution was given in the Assessment Report, other than that it was assumed that the carapace widths of recruits would range from 25 to 40 mm. No assessment of the sensitivity of model outputs to the size distribution that had been assumed was reported. **It is recommended that further consideration be given to the size range and distribution of recruits, and that three alternative size distributions might be considered, i.e. the most likely distribution and two distributions that are skewed to the left and right, respectively, of the first distribution and that are considered to bracket the feasible range of alternative size distributions.** The first of these distributions would be used when developing the base case model, while the other two distributions would be used to assess the sensitivity of model outputs to the range of feasible size distributions of recruits. Consideration should be given to the possibility that crabs with carapace widths less than 25 mm might molt more than once per year, and thus might recruit to the modelled population on each such molting occasion.

Growth data

The value of beta for the gamma distribution describing the variability of the molt increment is currently specified as the value of that variable for tanner crabs. While it may be appropriate to use the tanner crab value as the mean of a prior distribution of values for beta for snow crabs, its use should be phased out when it is possible to estimate the value of the parameter directly from snow crab data (after the collection of additional molt-increment data). If the gamma distribution is used to describe the variability in molt increment for individuals when constructing the size transition matrix used in the assessment model, it should probably also be used when calculating the likelihood used in fitting the growth model.

Selectivity for pot fishery retention

As processors only accept clean shell, fishers target locations where greater abundances of clean shelled crabs are available and, as a consequence, are less likely to fish in locations where greater abundances of older-shelled individuals may be found. The catchability of older shelled crabs by the pot fishery is thus likely to be less than that of the clean shelled crabs. Moreover, as the distribution by size of the older-shelled crabs in the locations fished may differ from that of the clean-shelled individuals, the selectivity curve for the capture of older-shelled crabs may differ from that for clean-shelled crabs. The probability of retention following capture is likely to be strongly related to shell condition for these older-shelled crabs. The current specification of selectivity and fishing mortality for the pot fishery does not take into account the differences in probability of capture and/or retention for clean-shelled and older-shelled snow crabs. It is important, however, to model the fact that crabs with old shell are less likely to be caught than clean-shelled crabs, and, if caught, less likely to be retained by fishers. This has considerably different implications for the model than if the probability of capture and retention is the same for both crabs with clean or old shell. More accurately modelling this aspect of the fishery would also allow the model to make use of observed data relating to shell condition.

ToR 4. Review of fishery dependent and fishery independent data inputs to the stock assessment.

Fishery-dependent data that were input to the assessment comprised time series of estimates of retained and discarded catches for the directed pot fishery for snow crabs, together with size, sex, maturity and shell condition data from samples of the retained and discarded catches within each year. A time series of estimates of discarded catches from the groundfish fishery, and their size compositions, were also input to the assessment.

Fishery-independent data included the time series of estimates of abundance of snow crabs calculated from the catches recorded by the NMFS during its annual systematic EBS surveys. The data relating to size, sex, maturity state, and shell condition of individuals in the samples from the survey catches in the different years of the survey were also used. The assessment also made use of data relating to the pre- and post-molt carapace widths for snow crabs that had been collected in the recent 2011 growth study, and the catch data resulting from two comparative trawl efficiency studies. The latter involved the use of a Bering Sea Fisheries Research Foundation (BSFRF) vessel that fished in the same survey grid cells (in the first study) as the NMFS survey vessels and (in the second study) side by side with the NMFS vessels. The BSFRF vessel towed a heavily-weighted *Nephrops* bottom trawl net while the NMFS vessels used standard 83-112 Eastern survey trawls

It is recommended that, in future assessment reports, the sources of the various data that are input to the stock assessment should be described in greater detail. Such descriptions should be brief, yet should provide details of the statistical design of the data collection programs, the data that were collected and recorded, and the methods that were used to analyse the data prior to their input to the assessment model. Changes in design, collected data, and/or methods of analysis should be described.

Data from the pot and trawl fisheries

The time series of estimates of landed catches of snow crab from the pot fishery is considered reliable as the data were apparently derived from the ticketing system. In this, the total mass of retained catch for each trip is determined when the landed catch is weighed at the point of sale and a ticket is created to record the details of that transaction.

Estimates of landings and discarded catches from the pot fishery, which were calculated using data from the mandatory observer program operated by the ADFG, were also input. Details of the observer program are described by Gaeuman (2013). In the 2012/13 fishing season, observers sampled three pots per day from two catcher-processor vessels and four pots per day from 22 of the 68 catcher vessels, the contents of which were counted, and, in the case of one pot, measured. An estimate of catch per unit of effort (CPUE) was then calculated from the observed catches in the sampled pots. This was then multiplied by the estimate of total fishery pot lifts derived from fish tickets, Daily Fishing Logs (DFLs) and confidential interviews to obtain an estimate of the total discarded catch (Gaeuman, 2013). The method of calculating the CPUE has changed over time. Gaeuman (2013) advises that, before 1997, it was calculated as total catch over all sampled pot lifts divided by the number of those pot lifts. Subsequently, the data were stratified by day within vessel, and later further stratified by vessel type, i.e. catcher-processor and catcher. While such changes will have introduced slight inconsistency into the time series of discarded catches, the impact on OFL estimates is likely to be small. Dr Turnock advised at the Review Meeting that the observer data are currently being re-analysed using a consistent method.

No details of the method by which the size, sex, shell condition, and maturity state (i.e. immature or mature) composition data collected by the observers for either retained or discarded catch from the pot fishery were combined to produce the data that were input to the model were provided in the Assessment Report or during the course of the Review Meeting. In this respect, it should be noted that Hoenig et al. (1987) advise that samples from different catches need to be appropriately weighted if the composition of the catch is to be estimated. **It is recommended that the method used to combine the composition data from the different observer samples be reviewed (and reported) to ensure that unbiased estimates of the composition of the retained and discarded catches from the pot fishery are obtained.**

Catch and size composition data relating to discards by the directed fishery were not derived by drawing samples directly from the crabs discarded by that fishery but represent the result of the observer randomly selecting a pot from those lifted during the day, examining the snow crabs that were caught in this pot, and then, presumably on the basis of his/her observations of the sorting carried out on the vessel by the fishers, classifying those crabs into two categories, i.e. those crabs that the observer considered would have been retained by the fishers and those that would have been discarded. The extent to which the observer modifies his criteria for classifying the crabs into the two categories to reflect the approach used by the crew of the fishing vessel on which the observer is working is unknown. Observer effect, i.e. the modification of fisher behaviour in response to the presence of observers, appears unlikely to be an issue as there is no regulatory constraint on discarding other than the minimum legal width of 78 mm, but the preferred market size is 101 mm and there is thus no incentive to retain crabs of less than the legal minimum carapace width. It is therefore reasonable to assume that the discarding practices prior to 1992, i.e. the year in which observers were first placed on fishing vessels, are the same as those post 1992, i.e. the total selectivity and retention curves by fishers did not change.

Estimates of discards by the groundfish fishery for recent years are based on data collected by on-board observers and thus are likely to be accurate. While the relatively high values of discards from this fishery that are recorded for 1973/74 and 1974/75, i.e. 13,630 and 18,8870 t (in Table 1 of the Assessment Report) warrant explanation, they did not affect the results of the assessment as the model was applied only to data from 1978 to 2013. As with the discard data from the pot fishery, **it is recommended that estimates of the variances of the estimates of discarded catch from the groundfish trawl fishery be calculated and input with the time series of discard estimates such that they are available for use in the model.**

A comment was made in the Review Meeting that the classifications of shell condition by ADFG observers might differ from those by NMFS research staff. This also raises the question of whether classifications vary over time or differ among individuals. It is recognised, however, that the consistency of the time series of classifications of shell condition made by each group should be maintained. Thus, if the classification criteria used by NMFS and ADFG do differ, it may be appropriate to accept that the difference exists rather than asking one group to modify its criteria**. It is recommended that a small study be undertaken to compare the classification criteria used by ADFG observers, observers from the groundfish fishery, and NMFS personnel, and to develop a reference collection of photographs of crabs with different shell conditions classified using the criteria employed by each group, such that future drift in criteria might be detected.**

The annual EBS trawl survey

As noted above, the time series of abundance data and data relating to the biological characteristics of the EBS population of snow crabs that have been produced by the annual NMFS summer trawl survey provide valuable information to the assessment and projection models. These input data are not without issue, however, and a number of concerns are discussed below.

In their 2013 Assessment Report, Turnock and Rugolo note that snow crabs are distributed on the continental shelf of both the Bering and Chukchi Seas, and are also found in the Western Atlantic Ocean, with the distribution extending as far south as Maine. Details of stock structure and/or connectivity between populations of snow crabs in the Bering, Chukchi, and Beaufort Seas were not reported and a brief literature search suggests that this may be a data gap. Such knowledge is important when defining the structure of a model that is to be used for stock assessment, and **it is recommended that future assessment reports should include a section discussing what is known and/or assumed regarding the stock structure of the snow crabs within the Bering Sea.**

The extent of the distribution of the eastern Bering Sea population of snow crabs into Russian waters is unknown, as is also the level of exploitation in these waters. High relative abundances of snow crabs were found on the U.S. side of the U.S.-Russian Convention Line during the 2010 eastern and northern Bering Sea surveys (Lauth, 2011). These survey results strongly suggest that the distribution of snow crabs extends beyond the Convention Line and that the abundance within Russian waters is likely to be of such magnitude that it should not be ignored when assessing the state of the snow crab stock. **It is recommended that, if possible, data on retained and discarded catches of snow crab west of the Convention Line, and the biological characteristics of those catches, should be obtained and that the implications of these data for the current assessment model should be considered.**

Data from continental slope surveys indicate that the distribution of snow crabs also extends beyond the southern boundary of the EBS survey area onto the slope but the abundance in this region is low and crabs are restricted to the 200-400 metre depth range. The impact on model results of excluding the snow crabs in this region is likely to be very small.

Based on the presentation by Dr Foy, the area covered by the eastern Bering Sea survey changed between 1980, 1981 1982, 1983-86, 1987, 1988, 1989, and 1990-2013 (same as 1988). The major effect of these changes was that, until 1988, the number of survey stations varied and gradually increased, and the survey area was extended to provide improved coverage of cells to the north of 61.2° N. The potential exists that the changes in area surveyed have introduced bias into the resulting estimates of snow crab abundance. If the assessment model is intended to provide a representation of the population of snow crabs within the bounds of the current survey grid, which is termed the 'EBS population' in this document, only survey input data since 1988 relate to that entire population. Information on the extent to which the earlier surveys represent the abundance and biological characteristics of the full EBS population might possibly be explored outside the assessment model by re-analysing the post-1990 data using only those cells that were surveyed in each of those earlier surveys and comparing the results with those obtained from the full survey area.

As demonstrated by the results of a 2010 survey in U.S. waters at the north of the Bering Sea (Lauth, 2011), the distribution of snow crabs extends beyond the northern boundary of the current survey area despite the extension of the EBS survey northward to improve its coverage. As a consequence, the availability of snow crabs within the survey area at the time of the annual survey is likely to vary inter-annually with changes in the spatial distribution of the population and the relative proportions of the snow crab population in the eastern, western (i.e. Russian waters) and northern regions of the Bering Sea.

In the course of his presentation, Dr Foy noted in his comments regarding the 2010 eastern and northern Bering Sea surveys that, in addition to the density of snow crabs in some cells in the northern Bering Sea being found to be much greater than those of cells in the EBS survey area, the size of the males at maturity was smaller, i.e. the carapace width following the terminal molt was less than 101 mm. Oransanz et al. (2007), citing Somerton (1981), advised that the mean size of mature females declined from approximately 70 mm at 55° N to 40 mm at 63° N. This suggests that individual snow crabs from different spatial locations may have experienced different growth rates and that the relationship between carapace width and the proportion of females of a given carapace width that are mature may vary among locations. This has implications for the collection of growth data and the variation in growth that is likely to exist among individuals from the full EBS population. Furthermore, crabs migrating into the EBS survey area from the northern Bering Sea between the time of the EBS survey and the start of the annual fishing season may have experienced slower growth and be smaller at age than crabs that were present in the EBS at the time of the survey.

Some of the snow crabs to the north of the EBS survey area are likely to migrate into the survey area, and thus ultimately contribute to the catches taken from the modelled stock and the reproductive potential of that stock, yet the magnitudes of these contributions are unknown, as is the proportion of the total (genetic) stock that is available to either the EBS survey or the snow crab fishery. Such movement is allowed for in the assessment model through the dispersion parameter of the gamma distribution that is used to distribute new recruits to the EBS population over the carapace width bins that are used in the model to store details of the abundance of crabs of that size and sex.

In addition to the survey trawls undertaken at standard stations within the systematic grid, multiple tows have been made within numerous survey grid cells. For example, corner stations were added in 1981 to provide higher density surveying in the region near the Pribilof Islands. In 1983, corner stations were also added to form a high density survey region near the St Mathew Islands. Hot spot surveys were introduced in 1990 and operated intermittently till 2010. These represented a form of adaptive sampling designed to improve the precision of abundance estimates for red king or tanner crabs for grid cells in which the standard survey tow at the station had yielded more than 100 legal-sized red king or tanner crab males, and thus would not have introduced bias for snow crabs. The Bristol Bay region was subjected to re-tows in 1999-2000 and 2006-12, when the reproductive cycle of red king crab was delayed due to the presence of colder water temperatures. With the exception of 1992 and 2008, additional trawl tows were also made each year between 1975 and 2013.

Concern was expressed at the Review Meeting that the consistency and accuracy of the trawl data may have been compromised by the use of the data obtained from the additional tows. Additional random trawls taken within the various survey grid cells, and used to improve the precision of the estimate of mean catch at the station for each of those grid cells, are unlikely to have introduced bias to the overall estimate of abundance for snow crabs. This is also true for the additional systematic hot spot trawls taken within a grid cell as the criterion for undertaking those additional trawls was independent of the catch of snow crabs that had been obtained at the station during the standard survey trawl. The data resulting from the introduction of corner stations and higher density sampling at the Pribilof and St Mathew Islands are also unlikely to have introduced bias as the decision to increase the sampling intensity in these locations was apparently not based on the density of snow crab. If concern persists, however, the hypotheses that the catches of the additional random, hot spot, or corner station samples differ from those of the standard trawls at the stations might be explored using a mixed effects model similar to that suggested for use when analysing the 2009 BSFRF-NMFS comparative trawl study (ToR 2).

In 1982, the net used in the EBS trawl survey was changed from a smaller 400-mesh Eastern to the 83-112 Eastern trawl that has been used consistently in all subsequent surveys (Weinberg, 2003). The assessment model currently analyses the survey and fishery data from 1978 to 2013. Because of the change in survey net, the assessment model employed a survey selection curve and catchability in 1978 to 1981 for each sex that differed from the selectivity curves and catchabilities for that sex in subsequent years.

Hybrid crabs

The Review Panel was advised that a small proportion of hybrid crabs were present in survey and fishery catches. These represented the progeny of mating between individuals of the snowcrab *Chionoecetes opilio* and the tanner crab *Chionoecetes bairdi*. The numbers of such crabs are sufficiently small that they need not be considered in the assessment or projection models.

BSFRF and NMFS comparative trawl efficiency studies

The input data from the 2009 and 2010 trawl efficiency studies conducted by BSFRF and NMFS appear sound.

Growth data

For a length-based fishery model to produce reliable estimates of stock status and variables such as the OFL, it must employ a growth curve that accurately describes the growth of individuals in the modelled population and the variability of that growth. Currently there are only 35 snow crabs for which observations of pre- and post-molt carapace widths are available, and these data were collected from ice-free regions of the eastern Bering Sea and thus may not be representative of the growth of individuals in the entire EBS snow crab population. Data on molt frequency of crabs of different sizes and sexes are not available. The paucity of data on growth is a serious deficiency as it increases the uncertainty of the outputs from the assessment and projection models. If the growth data are biased, the accuracy of the model outputs is likely to be affected.

Natural mortality

Natural mortality *M* is a key parameter for all stock assessment models, yet it is typically difficult to estimate. In the case of snow crabs, inability to age the crabs has hampered the development of estimates of natural mortality and the data that are available to allow estimation of this parameter are very limited. Although based on the best data that are available, the estimate that is used as the natural mortality of the female snow crabs and the mean of the prior distribution for males, i.e. 0.23 y^{-1}, is highly uncertain. Dr Turnock noted that he had attempted to estimate the value of *M* for females, but the resulting value was so low that it was considered infeasible. As the estimate of natural mortality is likely to influence strongly the estimates of B35% and F35% that are calculated by the assessment model, ongoing research studies to improve the estimate of M should be undertaken.

If the snow crabs did not undergo a terminal molt, length data, in combination with knowledge of growth, might have yielded an estimate of maximum age, and through this, an estimate of natural mortality. Such data may be used in the model, however, to estimate the period of time that has elapsed between recruitment and terminal molt for individuals in the different recruitment size bins. Although the state of the shell of a crab gradually deteriorates after the terminal molt, and criteria have been developed to allow classification of the shell into a number of shell condition categories, lack of information on the period spent within each shell condition category makes it impossible to determine the time that has elapsed since the crab undertook its terminal molt. Tagging studies to obtain information on mortality are hampered, in the case of the morphometrically-immature crabs, by the fact that tags such as toggle tags typically increase mortality at molting. In the case of the morphometrically-mature individuals, this particular factor is no longer an issue but, because of the reliance on the fishery to recapture tagged animals, the estimate of natural mortality is likely to be affected by avoidance by fishers of areas where the shell condition of the crabs is unacceptable to the market, or lack of detection and discard of older-shelled crabs if they happen to be recaptured.

The Review Panel noted that, if *M* is as low as estimated, there appear to be unusually few old-shell individuals. It was recognized, however, that clean shell crabs are likely to remain in this state for 1 to 3 years after the terminal molt. The possibility that mortality increases with the number of years that have elapsed following the terminal molt was discussed.

Maturity

The Assessment Report advises that, from 1989, data on morphometric maturity for males had been collected from survey catches, with chela measurements being taken from between 3,000 and 7,000 males each year. Subsamples for chela measurements were limited to between four and ten males from the catch at each survey station, but, in discussion at the Review Meeting, a comment was made that these individuals were not necessarily randomly selected. If this is the case, it would be worthwhile to review the sampling procedure with a view to improving it.

There was no indication in Gaeuman's (2013) description of the observer program that chela height measurements had been obtained from the males in the pots that were sampled by the pot fishery observer program. Consideration should be given to filling this apparent data gap.

Discard mortality

While the revised estimate of discard mortality, i.e. 30%, is likely to be more accurate than the previous estimate of 50% mortality, it remains a source of uncertainty. It is therefore pleasing to note that the alternative value of 50% was used to assess the sensitivity of the results of the assessment to possible error in this estimate.

The Review Panel discussed the possibility of using further tagging studies to obtain information on mortality and migration. The high level of discard mortality needs to be considered when planning such tagging studies.

ToR 5. Recommendation on research needs that would reduce uncertainty in key parameters used or estimated in the assessment.

It is suggested that priority for research should be given to:

- Improving the estimates of natural mortality, and determining whether this increases with time elapsed since the terminal molt.

- Increasing the number of observations of pre- and post-molt carapace width from molting crabs, covering as broadly as possible the ice-free region of the EBS when collecting immature crabs that are likely to molt.
- Improving the representation within the model of growth of immature snow crabs, and estimating variation in growth among individuals.
- Improving the knowledge of the relationships between MMB at mating and the reproductive outputs of the primiparous and multiparous females in the EBS, and how MMB relates to the reproductive potential of the population.

Note that, while these needs are discussed here, further comment is made in the discussion relating to ToR 6.

Growth data

The paucity of growth data has been identified as a serious concern, as the accuracy of the growth model is crucial if the dynamics of the stock are to be described correctly and outputs of the length-based model are to be reliable**. It is recommended that a research program is established to collect additional molt increment data annually in an ongoing program, at least until a sample of appropriate size is available to ensure that the estimates of growth parameters obtained when fitting the assessment model are of sufficient precision**.

It is currently assumed that individuals of the size range considered in the model, i.e. 25 – 135 mm, molt once per year. Research should be undertaken to confirm this assumption. This may require sampling throughout the year or the maintenance and monitoring of snow crabs in tanks within a laboratory.

Reproductive potential

The model currently employs the estimate of Mature Male Biomass (MMB), i.e. the biomass of morphometrically-mature males, at the time of mating as an indicator of the population's reproductive potential. It is known, however, that the distributions of primiparous females, i.e. mature, clean-shelled females, and multiparous males differ. As multiparous males typically occupy deeper water, the question had been posed as to whether these males migrated to the shallower depths occupied by the primiparous females such that, at the time of mating, they occupied the same regions as these females and could thus mate with them. Based on the results from a tagging study that employed data storage tags (DSTs), Dr Nichol advised that most multiparous males migrated inshore to the extent that, at the time of mating, they had the opportunity to mate with multiparous females. Multiparous males, however, had less opportunity to mate with primiparous females.

The relationship between MMB at the time of mating and the reproductive potentials of the primiparous and multiparous females is unknown. Nor is it known whether declines in MMB are reflected in increased prevalences of barren females or crabs with non-full clutches. Understanding the biology and dynamics of reproduction in the eastern Bering Sea snow crab population is essential if the appropriateness of the current indicator of reproductive potential is to be assessed. **It is recommended that further research be undertaken to understand better the relationship between MMB at the time of mating and the reproductive potentials of the primiparous**

and multiparous females and whether there is any link between MMB and the prevalence of barren females or variation in clutch fullness. It was suggested that further studies using both DSTs and conventional tags should be considered, in a workshop setting, to develop a tagging program to produce data that would address this question and provide additional information on the distribution and movements of terminally-molted crabs with shells of different ages, i.e. conditions.

Trawl surveys immediately before and after the fishing season

The spatial distribution of fishing activity is constrained by the extent of ice coverage, which varies inter-annually (Turnock and Rugolo, 2013 Assessment Report). In addition, because of movement, mortality, and molting, the abundances and distributions of snow crabs of different sizes and sexes that were present at the time of the annual summer survey have changed before fishing commences. The information available to the model might be considerably enhanced if, in addition to the current annual summer EBS survey, occasional (or annual) winter trawl surveys could be undertaken immediately prior to the opening of the fishing season and following the termination of that season, providing survey coverage of the ice-free area in which, in the case of the pre-fishing-season survey, the fishery is likely to be operating or, in the case of the post-fishing-season survey, the fishery has operated. Such surveys would provide fishery-independent abundance and size composition data that would be more directly comparable with the catch and size composition data from the pot fishery, overcoming some of the issues relating to the effects of availability, mortality, and migration that need to be considered when relating the fishery data to the data from the annual EBS survey.

Exploration of unusual parameter estimates and jitter test

Concern was expressed that a number of the parameter estimates presented in Table 10 of the Assessment Report appeared to be the initial specified values, e.g. "Female BSFRF 2009 Study area length at 95% of Q" = 60.00, and that these parameters had estimated SDs of 0.00, suggesting that the model might be unresponsive to these parameters. A request for a jitter analysis was considered but rejected in favour of producing an ADMB output displaying the gradients of the likelihood surface with respect to the various parameters at the point in the parameter space defined by the initial values of the parameter estimates. Dr Turnock ran this analysis, and reported that the model was indeed responsive to the parameters, but that a number of parameters had hit their bounds. Dr Turnock identified also that, because of a typographical error, the bounds reported in Table 10 of the Assessment Report were incorrectly aligned with the parameters with which they were associated.

It is recommended that a jitter test be undertaken and reported for future stock assessments, as this will identify problems with convergence and consistency of parameter and likelihood estimates.

Correlation matrix

To explore whether parameter estimates were likely to be confounded, Dr Turnock was requested to examine the correlation matrix that was output by ADMB when the assessment model was fitted. The resulting matrix revealed nothing of great concern. Only those parameters that would be expected to be highly correlated revealed absolute values of correlations that exceeded 0.8. The Panel recommended, however, that, rather than using a parameter in the selection curve that represented the length at which selectivity of the crabs was 95% of the maximum, a parameter representing the difference between the lengths at which selectivity was 95% and 50% of the maximum should be employed.

Parameter bounds

When fitting a model, bounds are often placed on parameters to constrain the search to the ranges of values that are considered feasible or to ensure numerical stability when searching. If, after fitting, the value of a parameter estimate is found to have converged to either its upper or lower bound, consideration should be given to specifying a broader range of feasible values, in which case the bounds should be reset. If, however, the current bounds represent the full range of feasible values, and the parameter estimate has converged to the bound, the model structure may be inappropriate (e.g. too complex), the code that implements the model may contain an error, or there may be problems with the data that were input. Consideration might also be given to the addition of an appropriate prior. **It is recommended that, when parameter estimates have converged to an upper or lower bound, as was the case with the snow crab assessment model, consideration is given to assessing whether model structure is appropriate, and, if so, adjusting the bound to a higher or lower bound within the range of feasible values or including an appropriate prior.**

Sensitivity and perturbation analysis

For the current assessment, the sensitivity of model outputs to discard mortality of 50% rather than 30% has been explored, together with sensitivity to estimation of growth using the molt-increment data from the 2011 growth study rather than not employing these data but estimating growth using prior distributions of the linear parameters (as used in the 2012 assessment). The sensitivity to other parameters, such as alternative values of the mean of the prior distribution for natural mortality or alternative values of beta for the size distribution of recruits, should also be explored. **It is recommended that the sensitivity of assessment and projection model outputs to uncertainty in key parameters or inputs be explored in greater detail**. Dr Cadigan suggested that perturbation analysis (Cadigan and Farrell, 2002, 2005) would provide an objective procedure to assess the sensitivity of output parameters, such as the OFL, to variation in input. This analysis would make use of the Hessian calculated by ADMB when fitting the assessment model.

Retrospective analysis

Many fishery models exhibit systematic trends in abundance and fishing mortality estimates for recent years as additional years of data are included in the assessments.

These are typically the result of model mis-specification. **It is recommended that a retrospective analysis be undertaken to determine whether the estimates produced for recent years by the snow crab assessment model are stable or exhibit trends indicative of a retrospective problem.**

Tension between data sets

In response to a request to explore the likelihood profiles of the component data sets for key parameters such as the estimates of natural mortality for mature and immature males, Dr Turnock produced the following results.

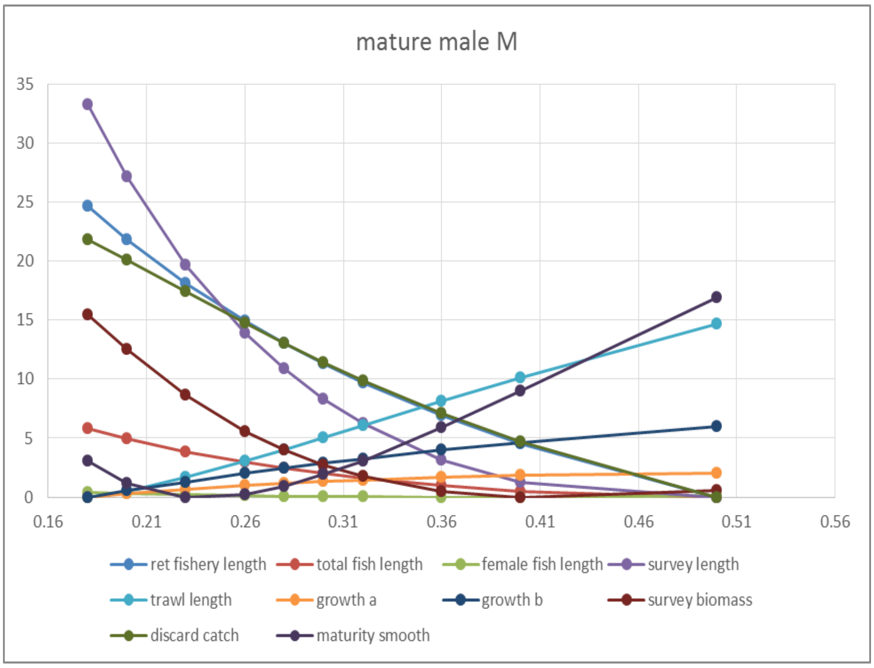

Figure 3. Profiles of the likelihoods of the components of the overall likelihood for the base model over a range of values for the estimate of *M* for mature males, where the likelihood of each component has been scaled by subtraction of the minimum value within that range. Note that the likelihoods of the different components are weighted (Table 11, Assessment Report).

The value of *M* for mature males, which was estimated by the model, was 0.386 y^{-1}. The profiles of the likelihoods of the component data sets (scaled by subtraction of the minimum value for that component within the range of values of *M* that were explored) suggest that female size composition data were uninformative, the trawl size composition data and growth data support an estimate of natural mortality that is less than 0.21 y^{-1}, the component labelled “maturity smooth” favoured a value of ~0.23 y^{-1}, survey biomass data supported a value of ~0.41 y^{-1}, and total fish size composition data, discard catch data, retained fish size composition data and survey size composition data favoured an even greater value (Fig. 3). The component likelihoods are weighted, however, and thus do not represent the true values of the likelihoods. Nevertheless, it can be concluded from the above inconsistencies that the point estimate of $M = 0.386$ y^{-1} represents a compromise between the values favoured by the different data sets. The tensions between the values of *M* that are supported by the different data sets suggests that there is a problem with model structure, i.e. the values predicted by the model are inconsistent with the observed data and there is thus a problem with either the model of the dynamics of the exploited stock or with the sub-models that represent the observation processes.

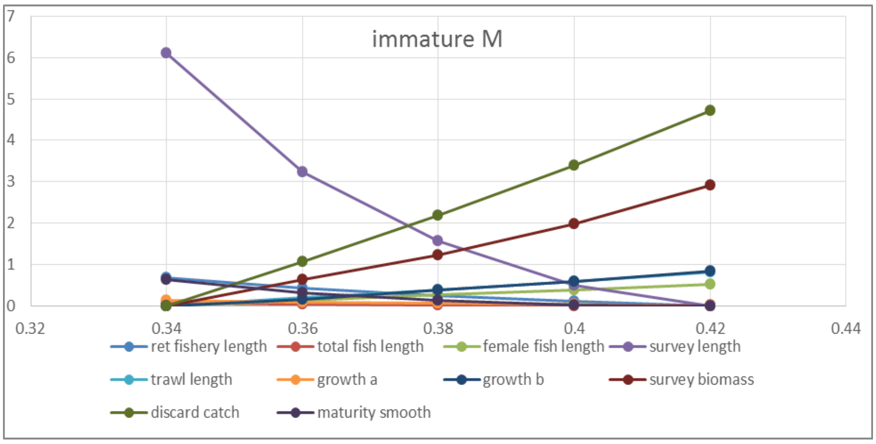

Figure 4. Profiles of the likelihoods of the components of the overall likelihood for the base model over a range of values for the estimate of *M* for immature snow crabs, where the likelihood of each component has been scaled by subtraction of the minimum value within that range. Note that the likelihoods of the different components are weighted (Table 11, Assessment Report).

Smaller values of natural mortality for immature snow crabs were supported by the discard catch data, survey biomass data, female size composition data, and "growth b" likelihood than by the size composition data for the surveys, retained catches, and trawl bycatches (Fig. 4). This inconsistency needs to be resolved by either correcting the model structure such that it more accurately represents the dynamics of the stock and its fishery or by correcting the way in which the model predicts the values of the various sets of observed data.

From the plots of the profiles of the likelihood of the different components, it would appear likely that the prior that was imposed on *M* is very influential in determining the value that is estimated when the model is fitted to the data. An unconstrained estimate of *M* would probably be greater than the value that was estimated.

Generalized Modeling for Alaskan Crab Stocks (Gmacs)

Continued development of the Generalized Modeling for Alaskan Crab Stocks (Gmacs) software is endorsed, as it offers the potential to explore more readily alternative model assumptions and sensitivities.

MSE

As demonstrated by Szuwalski & Punt (2013), a Management Strategy Evaluation framework for the snow crab population in the EBS provides a valuable simulation environment to explore issues with respect to the spatial distributions of the crabs, the survey and the fishery, and the movements of the crabs. It would be useful to assess the precision and accuracy of the estimates produced by the assessment model when applied to synthetic data generated using known values of parameters and to explore the impacts of deviations from the assumptions on which the assessment model is based. **It is recommended that consideration be given to constructing a generic MSE framework to accompany the Generalized Modeling for Alaskan Crab Stocks (Gmacs) software.**

ToR 6. Suggested research priorities to improve the stock assessment.

It is suggested that priority for research should be given to:

- Improving the estimates of natural mortality, and determining whether this increases with time elapsed since the terminal molt.
- Improving the description of growth of immature snow crabs, and its variation among individuals.
- Improving the knowledge of how morphometrically-mature males contribute to fertilization of primiparous and multiparous females in the EBS, and how this affects estimation of the reproductive potential of the population.

Natural mortality

Natural mortality is a key process in the models, and outputs of assessment and projection models are typically very sensitive to the value that is used for this parameter. In the case of the length-based EBS snow crab assessment model, the ability to obtain reliable estimates of natural mortality when fitting the model is hampered by the paucity of growth data, the fact that crabs undergo a terminal molt, and the fact that ice cover combines with the length and sex-dependent spatial distribution of the crabs to constrain the samples that can be taken and thus affects the representativeness of the growth data that are collected.

The technique of ageing crustacea using growth bands in their eye stalks, described by Kilada et al. (2012), offers the promise of obtaining age composition data for the EBS population of snow crabs. The results of the analysis undertaken by these authors suggested that formation of the bands in the eye stalks of snow crabs was not associated with molting, but occurred annually. In combination with data on growth and the attainment of morphometric maturity, it may be possible to explore whether the natural mortality of snow crabs increases with elapsed time following the terminal molt. The data obtained from eye stalk analysis is potentially a rich source of information that should improve the reliability of assessment results.

The Review Panel noted that data on the number of years for which individual crabs survive following their terminal molt would assist greatly in developing an estimate of natural mortality. It also noted the potential, however, that natural mortality might increase with elapsed time following the terminal molt. Because mortality is of such importance to the assessment, approaches other than the eye stalk method should also be investigated. For example, by tagging soft-shelled terminally-molted individuals with conventional tags and examining the shell condition of the recaptured individuals, it may be possible to determine estimates of the period spent within each of the intermediate shell condition categories, and the maximum period at liberty for recaptured individuals. **It is recommended that a workshop be held to design a tagging study that, by tagging soft-shelled terminally-molted snow crabs and/or crabs with shell condition SC2, would enable production of estimates of the time spent within each intermediate shell condition category and an estimate of the maximum time at liberty for recaptured snow crabs.**

Growth

As identified under Tor 5, there is an urgent need to collect additional growth data as, without these data, the outputs of the assessment and projection models are imprecise and potentially unreliable. The growth model is the foundation of the length-based model, and if this is not reliable, model outputs are unsound.

Snow crabs of the youngest sizes represented within the model are assumed to be probably around three to four years old, and those individuals that have not undergone a terminal molt are assumed to molt annually in the spring, i.e. March-April (Turnock and Rugolo, 2013 Assessment Report). There appears little evidence that molting of morphometrically-immature snow crabs within the modelled size range is indeed annual. Research should be undertaken to confirm that this assumption is valid.

Reproductive potential

The relationship between MMB at the time of mating and reproductive output by female snow crabs in unknown. Because of the nature of snow crab biology and the different spatial distributions and movements of the primiparous and multiparous females and the mature male snow crabs, there is a need to understand the factors affecting mating of the different groups, and the contribution of the different groups of female crabs to the reproductive output of the EBS population. Research on this topic needs to continue, possibly through further DST or conventional tagging studies.

5. Conclusions and recommendations

1. The estimates of both natural mortality and growth for Bering Sea snow crabs are imprecise. Reliable estimates of these two parameters are essential if the length-based assessment and projection models for the EBS snow crabs are to produce sound results. Further research studies need to be undertaken to provide the data necessary to improve the estimates of growth for the immature snow crabs and to produce reliable estimates of the mortality for the male and female snow crabs in the EBS population.
2. The possibility that the natural mortality of the snow crabs increases as the time since the terminal molt increases needs to be investigated.
3. A segmented linear model needs to be employed in the model to describe the growth of the immature snow crabs rather than the simple linear model that is currently used.
4. Data on the relationship between MMB at the time of mating and the reproductive outputs of the primiparous and multiparous females, and the relative contributions of those two groups of females to the reproductive potential of the stock, need to be obtained.
5. The current model descriptions lack clarity and there are gaps and inconsistencies in the mathematical description. It is recommended that the descriptions are revised to ensure that they are complete and accurately describe the underlying conceptual model and the calculations involved in projecting the state of the stock under different fishing mortality regimes. Once revised, there would be value in verifying that the ADMB code accurately implements the mathematical description of the model.

6. The ways in which the input data were collected and processed prior to input to the model need to be described in greater detail in the Assessment Report, such that their accuracy and precision can be assessed, and the accuracy of their representation in the assessment model can be evaluated.
7. To avoid the inconsistencies in survey data resulting from the use of different types of survey net in 1978-81 and the years that followed, it is recommended that the starting year considered in the model should be changed from 1978 to 1982.
8. The sensitivity of the model to the inclusion or exclusion of the data for the BSFRF-NMFS comparative trawling studies should be explored as the assumption that the *Nephrops* trawl net caught all snow crabs in its path is likely to be erroneous. If the BSFRF data are included, it is recommended that the results of the 2009 and 2010 comparative studies be analysed using a mixed effects model, rather than the approach that is currently employed in the model.

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Appendix 2: Copy of CIE Statement of Work

Statement of Work for Dr. Norm Hall

Statement of Work

External Independent Peer Review by the Center for Independent Experts

Bering Sea Snow Crab Stock Assessment Review

Scope of Work and CIE Process: The National Marine Fisheries Service's (NMFS) Office of Science and Technology coordinates and manages a contract providing external expertise through the Center for Independent Experts (CIE) to conduct independent peer reviews of NMFS scientific projects. The Statement of Work (SoW) described herein was established by the NMFS Project Contact and Contracting Officer's Representative (COR), and reviewed by CIE for compliance with their policy for providing independent expertise that can provide impartial and independent peer review without conflicts of interest. CIE reviewers are selected by the CIE Steering Committee and CIE Coordination Team to conduct the independent peer review of NMFS science in compliance the predetermined Terms of Reference (ToRs) of the peer review. Each CIE reviewer is contracted to deliver an independent peer review report to be approved by the CIE Steering Committee and the report is to be formatted with content requirements as specified in **Annex 1**. This SoW describes the work tasks and deliverables of the CIE reviewer for conducting an independent peer review of the following NMFS project. Further information on the CIE process can be obtained from www.ciereviews.org.

Project Description: The snow crab assessment was last reviewed by the CIE 2008. Since that time, the analyst has made a number of improvements to the model. These changes should be reviewed by an independent panel. The snow crab assessment is a high profile assessment which has undergone significant change in results due to incorporation of data on catchability of the survey net and estimation of natural mortality. This review would encompass the Bering Sea trawl survey data, additional survey data used in estimation of catchability, the stock assessment model structure, assumptions, life history data, and harvest control rule. The Terms of Reference (ToRs) of the peer review are attached in **Annex 2**.

Requirements for CIE Reviewers: Three CIE reviewers shall have the necessary qualifications to complete an impartial and independent peer review in accordance with the tasks and ToRs described in the SoW herein. The CIE reviewers shall have expertise in conducting stock assessments for fisheries management, and be thoroughly familiar with various subject areas involved in stock assessment, including population dynamics, size-structured models, harvest strategies, survey methodology, and the AD Model Builder programming language to complete the tasks of the scientific peer-review described herein. Familiarity with invertebrate stock assessment, knowledge of crab life history and biology, harvest strategy development is desirable. Each CIE reviewer is requested to conduct an impartial and independent peer review in accordance with the ToRs herein. The CIE reviewer's duties shall not exceed a maximum of 14 days conducting pre-review preparations with document review, participation in the panel review meeting, and completion of the CIE independent peer review report in accordance with the ToR and Schedule of Milestones and Deliverables.

Location of Peer Review: Each CIE reviewer shall participate and conduct an independent peer review during the panel review meeting scheduled at the Alaska Fisheries Science Center (AFSC) in Seattle, Washington during the tentative dates of January 21-24, 2014.

Statement of Tasks: Each CIE reviewer shall complete the following tasks in accordance with the SoW and Schedule of Milestones and Deliverables herein.

Tasks prior to the meeting: The contractor shall independently select qualified reviewers that do not have conflicts of interest to conduct an independent scientific peer review in accordance with the tasks and ToRs within the SoW. Upon completion of the independent reviewer selection by the contractor's technical team, the contractor shall provide the reviewer information (full name, title, affiliation, country, address, email, and FAX number) to the contractor officer's representative (COR), who will forward this information to the NMFS Project Contact no later than the date specified in the Schedule of Milestones and Deliverables. The contractor shall be responsible for providing the SoW and stock assessment ToRs to each reviewer. The NMFS Project Contact will be responsible for providing the reviewers with the background documents, reports, foreign national security clearance, and other information concerning pertinent meeting arrangements. The NMFS Project Contact will also be responsible for providing the Chair a copy of the SoW in advance of the panel review meeting. Any changes to the SoW or ToRs must be made through the COR prior to the commencement of the peer review.

Foreign National Security Clearance: The reviewers shall participate during a panel review meeting at a government facility, and the NMFS Project Contact will be responsible for obtaining the Foreign National Security Clearance approval for the reviewers who are non-US citizens. For this reason, the reviewers shall provide by FAX (not by email) the requested information (e.g., first and last name, contact information, gender, birth date, passport number, country of passport, travel dates, country of citizenship, country of current residence, and home country) to the NMFS Project Contact for the purpose of their security clearance, and this information shall be submitted at least 30 days before the peer review in accordance with the NOAA Deemed Export Technology Control Program NAO 207-12 regulations available at the Deemed Exports NAO website: http://deemedexports.noaa.gov/.

Pre-review Background Documents: Approximately two weeks before the peer review, the NMFS Project Contact will send (by electronic mail or make available at an FTP site) to the COR the necessary background information and reports (i.e., working papers) for the reviewers to conduct the peer review, and the COR will forward these to the contractor. In the case where the documents need to be mailed, the NMFS Project Contact will consult with the COR on where to send documents. The reviewers are responsible only for the pre-review documents that are delivered to the contractor in accordance to the SoW scheduled deadlines specified herein. The reviewers shall read all documents deemed as necessary in preparation for the peer review.

Tasks during the panel review meeting: Each reviewer shall conduct the independent peer review in accordance with the SoW and stock assessment ToRs, and shall not serve in any other role unless specified herein. **Modifications to the SoW and ToRs shall not be made during the peer review, and any SoW or ToRs modifications prior to the peer review shall be approved by the COR and contractor.** Each reviewer shall actively participate in a professional and respectful manner as a member of the meeting review panel, and their peer review tasks shall be focused on the stock assessment ToRs as specified herein. The NMFS Project Contact will be responsible for any facility arrangements (e.g., conference room for panel review meetings or teleconference arrangements).

The NMFS Project Contact will also be responsible for ensuring that the Chair understands the contractual role of the reviewers as specified herein. The contractor can contact the COR and NMFS Project Contact to confirm any peer review arrangements, including the meeting facility arrangements.

Tasks after the panel review meeting: Each reviewer shall prepare an independent peer review report, and the report shall be formatted as described in **Annex 1**. . If any existing Biological Reference Point or their proxies are considered inappropriate, or if an inappropriate model formulation is identified, the report should include recommendations and justification for suitable alternatives. If such alternatives cannot be identified, then the report shall indicate that the existing BRPs are the best available at this time. Additional questions and pertinent information related to the assessment review addressed during the meetings that were not in the ToRs may be included in a separate section at the end of an independent peer review report.

Contract Deliverables - Independent CIE Peer Review Reports: Each CIE reviewer shall complete an independent peer review report in accordance with the SoW. Each CIE reviewer shall complete the independent peer review according to required format and content as described in Annex 1. Each CIE reviewer shall complete the independent peer review addressing each ToR as described in Annex 2.

Specific Tasks for CIE Reviewers: The following chronological list of tasks shall be completed by each CIE reviewer in a timely manner as specified in the **Schedule of Milestones and Deliverables**.

1) Conduct necessary pre-review preparations, including the review of background material and reports provided by the NMFS Project Contact in advance of the peer review.
2) Participate during the panel review meeting at Seattle, Washington during FeJanuary 21through January 24, 2014.
3) Conduct an independent peer review in accordance with the ToRs (**Annex 2**).
4) No later than February 7, 2014, each CIE reviewer shall submit an independent peer review report addressed to the "Center for Independent Experts," and sent to Mr. Manoj Shivlani, CIE Lead Coordinator, via email to shivlanim@bellsouth.net, and CIE Regional Coordinator, Dr. David Die via email to ddie@rsmas.miami.edu. Each CIE report shall be written using the format and content requirements specified in Annex 1, and address each ToR in **Annex 2**.

Schedule of Milestones and Deliverables: CIE shall complete the tasks and deliverables described in this SoW in accordance with the following schedule.

17 December 2013	CIE sends reviewer contact information to the COR, who then sends this to the NMFS Project Contact
23 December 2013	NMFS Project Contact sends the stock assessment report and background documents to the CIE reviewers.
21-24 January 2014	Each reviewer shall conduct an independent peer review during the panel review meeting in Seattle, Washington
7 February 2014	CIE reviewers submit draft CIE independent peer review reports to the CIE Lead Coordinator and CIE Regional Coordinator
21 February 2014	CIE submits CIE independent peer review reports to the COR
28 February 2014	The COR distributes the final CIE reports to the NMFS Project Contact and regional Center Director

Modifications to the Statement of Work: This 'Time and Materials' task order may require an update or modification due to possible changes to the terms of reference or schedule of milestones resulting from the fishery management decision process of the NOAA Leadership, Fishery Management Council, and Council's SSC advisory committee. A request to modify this SoW must be approved by the Contracting Officer at least 15 working days prior to making any permanent changes. The Contracting Officer will notify the COR within 10 working days after receipt of all required information of the decision on changes. The COR can approve changes to the milestone dates, list of pre-review documents, and ToRs within the SoW as long as the role and ability of the CIE reviewers to complete the deliverable in accordance with the SoW is not adversely impacted. The SoW and ToRs shall not be changed once the peer review has begun.

Acceptance of Deliverables: Upon review and acceptance of the CIE independent peer review reports by the CIE Lead Coordinator, Regional Coordinator, and Steering Committee, these reports shall be sent to the COR for final approval as contract deliverables based on compliance with the SoW and ToRs. As specified in the Schedule of Milestones and Deliverables, the CIE shall send via e-mail the contract deliverables (CIE independent peer review reports) to the COR (William Michaels, via William.Michaels@noaa.gov).

Applicable Performance Standards: The contract is successfully completed when the COR provides final approval of the contract deliverables. The acceptance of the contract deliverables shall be based on three performance standards:
(1) The CIE report shall completed with the format and content in accordance with **Annex 1**,
(2) The CIE report shall address each ToR as specified in **Annex 2**,
(3) The CIE reports shall be delivered in a timely manner as specified in the schedule of milestones and deliverables.

Distribution of Approved Deliverables: Upon acceptance by the COR, the CIE Lead Coordinator shall send via e-mail the final CIE reports in *.PDF format to the COR. The COR will distribute the CIE reports to the NMFS Project Contact and Center Director.

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Annex 1: Format and Contents of CIE Independent Peer Review Report

1. The CIE independent report shall be prefaced with an Executive Summary providing a concise summary of the findings and recommendations, and specify whether the science reviewed is the best scientific information available.

2. The main body of the reviewer report shall consist of a Background, Description of the Individual Reviewer's Role in the Review Activities, Summary of Findings for each ToR in which the weaknesses and strengths are described, and Conclusions and Recommendations in accordance with the ToRs. The CIE independent report shall be a stand-alone document for others to understand the weaknesses and strengths of the science reviewed. The CIE independent report shall be an independent peer review of each ToRs.

3. The reviewer report shall include the following appendices:

   Appendix 1: Bibliography of materials provided for review
   Appendix 2: A copy of the CIE Statement of Work

Annex 2: Terms of Reference for the Peer Review

Bering Sea Snow Crab Stock Assessment Review

The report generated by the consultant should include:

1. A statement of the strengths and weaknesses of the Bering Sea snow crab stock assessment and stock projection models;
2. Recommend for alternative model configurations or formulations if required;
3. Recommendations of alternative model assumptions and estimators if required.
4. A review of fishery dependent and fishery independent data inputs to the stock assessment.
5. Recommendation on research needs that would reduce uncertainty in key parameters used or estimated in the assessment.
6. Suggested research priorities to improve the stock assessment.

Annex 3: Agenda for Panel Review Meeting

Bering Sea Snow Crab Stock Assessment Review

NOAA Alaska Fisheries Science Center
7600 Sand Point Way NE, Seattle, WA 98115
Contact: jack.turnock@noaa.gov Phone: 206-526-6549

21-24 January 2014

Tuesday, January 21

09:00 Welcome and Introductions
09:15 Role of chair and reviewers, terms of reference
09:30 Overview (species, surveys, fishery, catch levels, bycatch)
10:00 Biology (growth, natural mortality, diets, spawning areas, nursery areas, maturity curves, mating, molting frequency)
11:00 Field experiments on escapement, discard mortality, tagging
11:30 Age Determination, shell condition
12:00 Lunch
13:00 Biology continued
14:00 Harvest control rules and overfishing definition
15:00 Ecosystem considerations - Predation, prey
16:00 Summary of on-going research
Egg viability
Migrations and movement
Larval drift
Spatial modeling
Management Strategy Evaluation

Wednesday, January 22

09:00 Survey methodology and analysis
12:00 Lunch
13:00 Description of stock assessment and projection model

Thursday and Friday, January 23-24

Reviewer discussions with assessment authors. Review of requested model runs if required.