**CIM Best Practice Guidelines for Resource and Reserve Estimation for Lithium Brines**

These guidelines were prepared by the Sub-Committee on Best Practice Guidelines for Resource and Reserve Estimation for Lithium Brines. The procedures and concepts presented below represent the state of the current understanding of the best practices that are applicable to the estimation of brine resources and brine reserves for lithium and other valuable metal ions in brine deposits. It is acknowledged that these practices are likely to evolve and improve with time as additional experience is gained from this deposit type. It is anticipated that these improvements will be the subject of and included in subsequent revisions of these Best Practices.

Brine deposits have received increasing attention from exploration companies as sources of lithium due to rapid expansion of production of lithium ion batteries for portable electronic applications, and development of electric battery powered vehicles. Lithium-bearing mineral brines are also attractive as sources of potassium and boron due to the presence of these elements in most brine deposits and the requirement to remove the elements prior to lithium recovery.

Brines are unique amongst mineral deposits because the valuable elements are contained in a mobile environment, and both brine composition and grade have a temporal component, before and during extraction. These factors present unique problems in exploration and sampling in addition to estimating the resources and reserves of lithium brine deposits.

Evaluation of brine resources is complex and requires participation by a variety of Qualified Persons (QPs) such as geologists, hydrogeologists, geochemists and chemical engineers, all with relevant experience in salar geology and brine processing. Therefore the preparation of resource and reserve estimates for brine resources should be carried out by a multi-disciplinary team and the Technical Reports disclosing the results of these estimates should reflect the inputs of that multi-disciplinary team.

## APPLICABILITY OF NI 43-101 TO BRINE PROJECTS

**National Instrument 43-101 –** ***Standards of Disclosure for Mineral Projects*** (**NI 43-101**)**,** and the definition standards and guidelines of the Canadian Institute of Mining, Metallurgy and Petroleum (**CIM**) has set out the specific requirements and the framework for reporting information of a scientific or technical nature for solid mineral deposits. Brine projects, while differing in the nature of the target mineral, face the same technical disclosure issues as more traditional projects. Issuers should strive to provide a level of clarity and technical detail meeting the spirit and intent of NI 43-101.

## Consideration as Industrial Minerals

The valuable metal ions in brine deposits are typically lithium, potassium and boron. Other elements or compounds may also be recovered and sold, typically in the form of salts such as sodium chloride, magnesium chloride, sodium sulphate, magnesium sulphate or double salts of potassium, magnesium or sodium. Regardless of the final product form, the products from brine processing exhibit the characteristics of industrial minerals. Accordingly, for the purposes of reporting brine resources and brine reserves estimates using the framework of the reporting standards of NI 43-101, technical reports for brine deposits should follow the specific provisions related to industrial minerals detailed in the ***Best Practices Guidelines for Reporting Mineral Resources and Mineral Reserves for Industrial Minerals*** as issued by the CIM.

## RESOURCE/RESERVE ISSUES SPECIFIC TO SALARS

### Type of Salar

Two types of salars (i.e. salt flats) are generally recognized: mature halite salars and immature clastic salars.

Mature salars are dominated by thick sequences of nearly pure halite, sometimes with gypsum zones. Immature salars are dominated by thick sequences of clastic material with lesser amounts of halite and gypsum. The evaporitic or clastic sequences tend to be deposited in a typical concentric shell-like sequence from gravel outside, through sand, silt, and clay, followed by carbonate, gypsum and finally halite in the center. Depending on the tectonic and climatic history of the basin, typical sequences will be disrupted, repeated or modified.

The basin (salar) infill is necessarily composed of one or more aquifers (if a brine prospect is to exist) that may be separated by aquitards or aquicludes. The brine is hosted by the aquifers, which may be unconfined, semi-confined or confined. The brine prospect normally lies in what has been termed the nucleus of the salar.

The boundary (marginal) conditions between the salar infill deposits and the underlying or surrounding basement are of considerable importance in understanding existing hydrological conditions and how the brine body will react during extraction.

It is important that the Qualified Person ("QP") estimating brine resources and brine reserves understand and explain in the resource report the impact of salar type on salar boundary conditions, brine chemistry, salar porosity and permeability, and salar transmissivity on resource volume, resource recoverability and resource quality.

### Brine Body Definition

The brine body is defined by its much higher density (usually >1.1 gm $cm^{-3}$) than any surrounding fluids, and there is usually a relatively rapid gradient from near-fresh water to brine around the margins and at depth within the salar. It is essential that the extent of the brine body is defined by the density gradient and its variation with depth around the margins of the salar. The brine body may generally be considered fossil with respect to current hydrologeological conditions, since turnover between the brine body and surrounding 'fresh' water will be controlled and limited by evaporative losses from the surface of the nucleus, which are orders of magnitude smaller than the evaporative losses from marginal 'fresh' water. The extent of the brine body may be determined by both appropriate geophysical and drilling/sampling methods.

Within the brine body variations in fluid chemistry can be expected, especially if the brine has more than one source. The concentration of the elements of interest and any additional elements that might impact brine processing must be known with appropriate levels of detail and accuracy throughout the brine body. Obtaining samples uncontaminated by drilling fluid and/or over (or under) lying brine can be particularly difficult, and repeat sampling should always be used to assess the provenance of at least a selection of samples. Additional sampling techniques such as double packer installation and extraction, core pore fluid extraction, low flow sampling, piezometer installation and purging should be considered. The use of multiple techniques obviously adds to the reliability of the resource/reserve estimate.

The estimation of resources and reserves requires definition of the chemical distribution within the brine aquifer which is a function of both the shape of the aquifer and the boundary conditions as they affect possible interactions between the brine and the surrounding groundwater. The boundaries of the brine body will be controlled by the transition to fresh water. This boundary can be approximately determined using time-domain electromagnetic or audio magneto-telluric surveys. Reflective seismic surveys may also be a useful tool for determining the presence of layers within the brine body and the depth of the salar, especially in the case of clastic salars. Microgravity surveys can also provide useful data on salar dimensions. Resistivity surveys can be helpful in defining aquifer zones, although the technique is more applicable to clastic salars with intervening fresh water and brine horizons (where conductivity differences can be noted) than for halite salars (where the high conductivity overwhelms the response).

Analytical techniques are beyond the scope of this document, but it should be noted that many 'water laboratories' are not familiar with super-concentrated brines which can be difficult to analyze with precision and accuracy. Appropriate use of standards, duplicates, blanks and check samples should always be incorporated into the QA/QC program.

**Salar Shape**

All other factors being equal, larger and more circular salars are better able to support long-term extraction than smaller or elongate salars. The ratio of extraction volume to storage volume is a key determinant of production life as in general, only approximately one-third of the total brine volume can be recovered, the balance being retained within the pores of the salar matrix or otherwise not subject to removal by pumping.

The basement topography of the salar can affect the hydrology, water balance, porosity and permeability of the brine deposit. Determination of the impact of ridges, faults and other structural and topographic features that may affect on brine movement and quality within the salar is required.

**Brine Hydrology and Water Balance**

An understanding of the hydrology of the brine and the water balance of the aquifer and the brine itself is necessary for the proper evaluation of brine resources and brine reserves. The catchment basin inflow, the evaporation of dilute salt laden fresh water, and the (potential) density driven convection currents within the brine body affect the brine chemistry and brine disposition over time. The QP must understand these dynamic relationships and provide an analysis of their impact on the brine resource/reserve estimate.

**Porosity, Permeability, Hydraulic Conductivity, Transmissivity, Anisotropy and Resistance**

Salar brines are contained within a matrix in which the porosity, permeability, brine composition, and hydrostratigraphic characteristics such as conductivity, transmissivity, anisotropy, and resistance may vary with the passage of time. These parameters are influenced by the type of salar and the nature of the matrix. It is essential that these relationships be understood and measured to a sufficient degree of detail to enable the preparation of brine resource and brine reserve estimates.

Porosity measurements should be reported using several parameters. It is recommended that the following be reported, with a clear distinction and discussion of each in relation to resource and reserve estimates:

- Total Porosity ($P_t$): total volume of pores within a unit volume of aquifer material
- Effective Porosity ($P_e$): drainable interconnected pore volume of aquifer material; $P_e < P_t$
- Specific Yield ($S_y$): yield of drainable fluid obtained under gravity flow conditions from the interconnected pore volume; $P_e = S_y + S_r$
- Specific Retention ($S_r$): retained fluid in aquifer material; $S_y$ < or > $S_r$
- Permeability (hydraulic conductivity)
- Transmissivity
- Storativity
- Diffusivity

The Specific Yield parameter should be used as the measure of the brine resource and brine reserve. In estimating Specific Yield, the QP must be cognizant of the relevance of the following:

Permeability and hydraulic conductivity are related factors providing a quantitative measure of the ease of movement of a fluid through a matrix when subjected to a hydraulic gradient. Permeability is defined qualitatively as the ease with which liquids or gases penetrate or pass through a matrix. Intrinsic permeability ($K_i$) is a quantitative property of a porous material and is controlled by the pore geometry of the porous medium alone. Care must be taken in defining and reporting these terms so as to avoid confusion.

Hydraulic conductivity is a measure of a material to transmit a fluid when subjected to a hydraulic gradient. Transmissivity is defined as hydraulic conductivity multiplied by aquifer thickness and is a measure of the availability of fluid within a given thickness and time interval. An aquifer may consist of multiple layers with different transmissivities in the horizontal and vertical dimensions. These differences must be considered when developing resource and reserve estimates.

The conductivity and transmissivity of an aquifer can be determined from pumping tests. Fine grained clastic sediments such as clay have low permeability and low transmissivity. The converse is true for coarse grained clastics. Clastic salars can have zones of both high and low permeability and transmissivity which can change rapidly with changes in lithology. Accordingly, sufficiently closely spaced sampling to establish the relationship between lithology, specific yield, permeability and transmissivity is required. The use of packers or other devices to isolate specific horizons is generally required for effective sampling. In mature halite salars, permeability and transmissivity values can be very high in the upper horizons due to the presence of cracks and fissure, but typically decrease significantly with depth due to compaction and crystal growth.

Resistance plays a role in aquifers where a sequence of layers occurs with varying horizontal permeability so that horizontal flow is found mainly in the layers with high horizontal permeability while the layers with low horizontal permeability transmit the water mainly in a vertical sense.

An aquifer is called *semi-confined* when a saturated layer with a relatively small horizontal hydraulic conductivity (the semi-confining layer or aquitard) overlies a layer with a relatively high horizontal hydraulic conductivity so that the flow of groundwater in the first layer is mainly vertical and in the second layer mainly horizontal.

The resistance of a semi-confining top layer of an aquifer can be determined from pumping tests. When calculating flow to drains or to a well field in an aquifer with the aim to control the water table, the anisotropy is to be taken into account; otherwise the result may be erroneous.

Hydraulic conductivity ($K$) is one of the most complex and important of the properties of aquifers as the values found in nature:

- range over many orders of magnitude (the distribution is often considered to be lognormal),
- vary a large amount through space (sometimes considered to be randomly spatially distributed, or stochastic in nature),

- are directional (in general *K* is a symmetric second-rank tensor; e.g., vertical *K* values can be several orders of magnitude smaller than horizontal *K* values),
- are scale dependent (testing a $m^3$ of aquifer will generally produce different results than a similar test on only a $cm^3$ sample of the same aquifer),
- must be determined indirectly through field pumping tests, laboratory column flow tests or inverse computer simulation, (sometimes also from grain size analyses), and
- are very dependent (in a non-linear way) on the water content, which makes solving the unsaturated flow equation difficult. In fact, the variably saturated *K* for a single material varies over a wider range than the saturated *K* values for all types of materials

The QP should provide adequate detail on the method(s) used to determine each parameter, and analytical methods. The results should be fully explained by the QP(s) using language that can be understood by the investing public. Porosity, permeability and hydraulic conductivity values should preferentially be determined using two independent methodologies.

**Brine Chemistry**

Brine chemistry has a direct and significant impact on the economic potential of a brine deposit and thus on determination of brine resources and brine reserves. It is essential for the QP(s) to understand the chemistry of the brine in terms of the concentrations and distribution both laterally and vertically of the valuable metal ions. In addition, the QP(s) must understand and report on the relationships between the various cations and anions that may have an impact upon the ease of brine processing and the recovery of the metal ions of interest. Furthermore; when reporting brine reserves, the QP(s) must understand and report on the changes in brine chemistry over time due to both inflows into the system from the greater catchment basin, and as a result of the response of the brine body to extraction.

**Neighbouring Properties**

Salars can be of considerable size and multiple operators may be present on any individual salar. Property rights in brine deposits are defined by nominally vertical planes between surface coordinates. However, due to the dynamic nature of the brines, brine extraction operations can have effects beyond the corresponding property limits. The QP(s) must understand and report on the potential impact of extraction operations on adjacent properties and make provision for necessary setbacks and reductions in the corresponding volumetric measure of the potentially available brine.

**Temporal Effects**

The composition of brines is subject to temporal effects due to changes in fluid flows resulting from both external (catchment basin) effects and internal (extraction induced) effects. As noted above, brine composition will change in response to changes in the catchment basin water balance and basin hydrology. These changes are generally slow if the brine body is not placed under dynamic stresses such as those associated with pumping. The QP(s) must understand and report on the potential for temporally induced effects on brine chemistry and brine volume.

## ESTIMATION OF RESOURCES AND RESERVES

The essential elements of brine resource or brine reserve determination for a salar are:

- Definition of the aquifer geometry
- Determination of the Specific Yield ($S_y$) of the aquifer
- Determination of the concentration of the elements of interest
- Determination of permeability, hydraulic conductivity, transmissivity, storativity, dispersivity and other factors

Resources may be defined as the product of the first three parameters. The use of specific yield allows the direct comparison of brine resources from the widest range of environments. Specific yield is to be estimated for separate layers in the aquifer if these are separated by impermeable layers.

Aquifer geometry is a function of both the shape of the aquifer, the internal structure and the boundary conditions as they affect possible interactions between the brine and the surrounding groundwater. Aquifer geometry and boundary conditions can be established by drilling and geophysical methods. Hydrogeological analyses are required to establish catchment characteristics such as ground and surface water inflows, evaporation rates, water chemistry and other factors potentially affecting the brine reservoir volume and composition in-situ and under pumping conditions. Monitoring stations for hyrdrometeorological parameters are required to determine base line conditions and a measure of comparison over time.

Drilling will be required to obtain samples to estimate the salar lithology, hydrostratigraphy, porosity, permeability, specific yield and grade variations both laterally and vertically. The selection of drilling methods, drill hole spacing, and drilling depths is the responsibility of the QP(s). The suggestions by Houston et al (2011) provide useful guidelines. In developing the drilling and sampling program, the QP(s) must be cognizant of the following considerations:

- The drill density and drill method should reflect the differences in matrix conditions and stratigraphy between mature halite salars and immature clastic salars;
- The drilling technique should be conducive to recovery of samples for both porosity/permeability and brine chemistry determination;
- High core recovery is essential in locations with rapid changes in lithology and possible rapid changes in aquifer porosity/permeability and brine chemistry characteristics;

- Core samples should be collected in as undisturbed condition as possible for laboratory determination of porosity and permeability;
- Geophysical logging should complement lithostratgraphic logging of core;
- Sample intervals should be designed to match observable changes in stratigraphy and porosity/permeability at the time of drilling;
- Sampling protocols must be selected that can accurately determine the in-situ location of the sampled intervals;
- Specific Yield (Sy) should be determined using two independent methodologies;
- Pumping tests must be of sufficient duration to assess permeability, fluid yield and brine chemistry over a reasonable range of pumping parameters, time and variations in lithology. Packer tests should be used for different aquifer zones;
- Details of the specific QA/QC standards and procedures used in determination of porosity, permeability, conductivity, transmissivity and analysis of the brines must be reported.

It is recommended that total porosity and effective porosity are not used for resource estimation since not only is the ratio of total (and effective) porosity to specific yield different for different aquifer materials, but the use of these parameters lead to unrealistic production expectations. Furthermore, assumed values (as opposed to measured values) for any parameter should be unacceptable for brine resource estimation at any level.

Estimation of brine reserves requires the incorporation of additional parameters. These include permeability (strictly hydraulic conductivity), transmissivity, storativity (a function of fluid and aquifer compressibility), and dispersivity. Information is also required on the efficiency of the extraction system (wells or trenches). Finally, elements of the water balance outside the nucleus, in the margins and surrounding bedrock must be known to an acceptable degree.

Digital simulation groundwater flow models are available that enable production forecasts to be made. It must be noted that the modeling of brine fluid flow is at the limit of the current capability of available models since the interaction of brine and fresh water is effectively two phase: they are immiscible under laminar flow conditions where the density difference exceeds around 0.05 gm $cm^{-3}$. The specific modeling package used in estimation of fluid flows, changes in brine chemistry over time and changes in brine volumes is to be described in the brine resource/reserve technical report.

When reporting Indicated and Measured Brine Resources the QP(s) must bear in mind that only those resources which are or may become recoverable under reasonably assumed technical and economic conditions should be included in the resource estimate. The estimation of Proven and Probable Reserves must take into consideration the requirement for sufficient test work to establish suitable process flow sheets for recovery of lithium and other valuable metal ions and the associated recovery factors and estimation of capital and operating costs in conformance with the CIM Best Practice Guidelines for Mineral Processing.

Brine resources and brine reserves are to be reported as available cubic metres of brine with a grade in mg $L^{-1}$, ppm, or weight percent (the latter two units requiring corresponding density values) for the valuable elements such as Li, K and B. The methodology for determination of cut-off values used in resource/reserve estimation is to be clearly described. Reporting of lithium carbonate or other lithium compound equivalents in the resource or reserve estimate is discouraged. However, such values may be reported elsewhere in the technical report.

**SUMMARY**

A technical report prepared in respect of a brine project must reflect the issues outlined in these guidelines that are specific to brine-hosted deposits and as detailed in OSC Staff Notice 43-704 *Mineral Brine Projects and National Instrument 43-101 Standards of Disclosure for Mineral Projects* dated July 22, 2011 (see modified table below):

| **Issue** | **Form 43-101F1 Item** | **Considerations for Mineral Brine Projects** |
|---|---|---|
| Mineral Rights | Item 4: Property Description and Location | Nature of the mineral tenure and any potential risks and uncertainties regarding “ownership” of the brine. |
| Climate | Item 5: Accessibility, Climate, Local Resources, Infrastructure and Physiography | Relevant meteorological data such as solar radiation, precipitation, wind, etc. |
| Geology and Mineralization | Item 7: Geological Setting and Mineralization | Hydrological aspects of the property such as surface and groundwater, water balance, and geology of the aquifer; characteristics of the brine body such as its geometry, chemical composition, variability, grade, etc. |
| Deposit Types | Item 8: Deposit Types | Characteristics of the host salar (salt flat), associated hydrogeology, aquifer boundaries, physical properties, etc. |
| Sampling | Item 11: Sample Preparation, Analyses and Security | Controls and protocols for brine sampling and preservation and determination of key variables such as porosity, specific yield, permeability, etc. |
| Brine Resources | Item 14: Mineral Resource Estimates | Key variables such as brine volume and grade, aquifer geometry, effective porosity, specific yield, flow rate, recoverability, etc. in order to meet the definition of reasonable prospects of economic extraction. |
| Brine Reserves | Item 15: Mineral Reserve Estimates | Key variables such as hydraulic conductivity, recovery, brine behaviour and grade variation over time, etc. and fluid flow simulation models in order to demonstrate that economic extraction can be justified. |
| Mining Method | Item 16: Mining Methods | Relevant information related to the design of the well field, infrastructure, pumping rate, brine body response to extraction, etc. |

Evaluation of brine resources is complex and requires participation by a variety of QPs such as geologists, hydrogeologists, geochemists and chemical engineers with relevant experience in salar geology and brine processing. Therefore, the preparation of brine resource and brine reserve estimates for brine deposits should be carried out by a multi-disciplinary team and the technical reports disclosing the results of these estimates should reflect the inputs of that multi-disciplinary team.

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**Acknowledgements**

The author is grateful for the comments and reviews provided by John Houston, members of the CIM Mineral Resource and Mineral Reserve Committee and the CIM Best Practices Committee, and the contribution of the technical staff of the Ontario Securities Commission in development of these Best Practices Guidelines.

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