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DEVELOPMENT OF A TECHNOLOGY FOR REPROCESSING SPENT ZEOLITES USED IN GAS DEHYDRATION: A REVIEW AND TECHNOLOGICAL ASSESSMENT

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Abstract: *Zeolite molecular sieves are widely used for deep dehydration of natural gas because of their high affinity for water, well-defined micropore structure and ability to achieve very low outlet water concentrations. During long-term cyclic operation, however, the adsorbent gradually loses performance as a result of hydrothermal aging, carbonaceous deposits, adsorption of methanol and heavier hydrocarbons, pore blockage, binder deterioration and mechanical attrition. Complete replacement of the molecular sieve bed produces a significant solid-waste stream even though a substantial part of the spent material may retain crystalline structure and recoverable adsorption capacity. This review and technological assessment summarizes recent data on the deactivation and regeneration of 3A, 4A, 5A and 13X molecular sieves used in gas dehydration and proposes an integrated reprocessing route. The proposed route includes feed identification and segregation, removal of fines, analytical diagnosis, low-temperature drying, thermal desorption, controlled oxidative removal of carbonaceous residues when justified, cooling under dry gas, grading, water-adsorption testing and mechanical quality control. Depending on the recovered performance, regenerated material may be returned to dehydration service, redirected to less demanding adsorption duties, or converted into an aluminosilicate secondary raw material. The article is literature-based and does not report original plant trials; therefore, the temperature windows and acceptance criteria are presented as screening ranges that must be validated for the exact commercial zeolite, binder and contamination profile.*

Keywords: *natural gas dehydration; molecular sieve; zeolite; spent adsorbent; regeneration; reprocessing; thermal treatment; coke removal; circular economy.*

GAZNI QURITISHDA ISHLATILGAN ISHLATILGAN SEOLITLARNI QAYTA ISHLASH TEXNOLOGIYASINI ISHLAB CHIQISH: SHARH VA TEXNOLOGIK BAHOLASH

Annotatsiya: *Seolit molekulyar elaklar suvga yuqori moyilligi, aniq shakllangan mikrog‘ ovak tuzilishi va chiqish oqimidagi suv konsentratsiyasini juda past darajagacha kamaytirish imkoniyati tufayli tabiiy gazni chuqur quritishda keng qo‘ llaniladi. Biroq uzoq muddatli siklik ishlash jarayonida adsorbent gidrotermik qarish, uglerodli cho‘ kindilar hosil bo‘ lishi, metanol va og‘ ir uglevodorodlarning adsorbsiyalanishi, g‘ ovaklarning tiqilib qolishi, bog‘ lovchi moddaning yemirilishi hamda mexanik ishqalanish natijasida o‘ z samaradorligini asta-sekin yo‘ qotadi. Molekulyar elak qatlamini to‘ liq almashtirish katta miqdorda qattiq chiqindi hosil qiladi, holbuki ishlatilgan materialning muayyan qismi kristall tuzilishini saqlab qolishi va qayta tiklanishi mumkin bo‘ lgan adsorbsion sig‘ imga ega bo‘ lishi mumkin. Mazkur sharh va texnologik baholashda gazni quritishda qo‘ llaniladigan 3A, 4A, 5A va 13X molekulyar elaklarning faolsizlanishi va regeneratsiyasi bo‘ yicha so‘ nggi ma’lumotlar umumlashtirilgan hamda kompleks qayta ishlash texnologiyasi taklif etilgan. Taklif etilayotgan texnologiya xomashyoni aniqlash va saralash, mayda zarrachalarni olib tashlash, analitik diagnostika, past haroratda quritish, termik desorbsiya, zarur hollarda uglerodli qoldiqlarni nazorat ostida oksidlovchi usulda olib tashlash, quruq gaz muhitida sovitish, fraksiyalash, suvni adsorbsiyalash qobiliyatini sinash va mexanik sifat nazoratini o‘ z ichiga oladi. Qayta tiklangan materialning xususiyatlariga qarab, regeneratsiyalangan seolit quritish jarayoniga qaytarilishi, talablari nisbatan past bo‘ lgan adsorbsion jarayonlarga yo‘ naltirilishi yoki alumosilikat ikkilamchi xomashyoga aylantirilishi mumkin. Maqola adabiyotlar sharhi asosida tayyorlangan bo‘ lib, unda sanoat qurilmasidagi original sinovlar natijalari keltirilmagan. Shu sababli harorat diapazonlari va qabul qilish mezonlari aniq tijoriy seolit turi, bog‘ lovchi modda hamda ifloslanish tarkibi uchun alohida tasdiqlanishi lozim bo‘ lgan dastlabki baholash diapazonlari sifatida taqdim etilgan.*

Kalit so‘ zlar: *tabiiy gazni quritish; molekulyar elak; seolit; ishlatilgan adsorbent; regeneratsiya; qayta ishlash; termik ishlov berish; koksni olib tashlash; aylanma iqtisodiyot.*

РАЗРАБОТКА ТЕХНОЛОГИИ ПЕРЕРАБОТКИ ОТРАБОТАННЫХ ЦЕОЛИТОВ, ИСПОЛЬЗУЕМЫХ ДЛЯ ОСУШКИ ГАЗА: ОБЗОР И ТЕХНОЛОГИЧЕСКАЯ ОЦЕНКА

Аннотация: *Цеолитовые молекулярные сита широко применяются для глубокой осушки природного газа благодаря их высокой сродству к воде, хорошо сформированной микропористой структуре и способности обеспечивать очень низкую концентрацию воды на выходе. Однако при длительной циклической эксплуатации адсорбент постепенно теряет свои эксплуатационные характеристики вследствие гидротермического старения, образования углеродистых отложений, адсорбции метанола и тяжёлых углеводородов, блокировки пор, разрушения связующего и механического истирания. Полная замена слоя молекулярного сита приводит к образованию значительного потока твёрдых отходов, несмотря на то, что существенная часть отработанного материала может сохранять кристаллическую структуру и восстанавливаемую адсорбционную способность. В настоящем обзоре и технологической оценке обобщены современные данные о дезактивации и регенерации молекулярных сит 3A, 4A, 5A и 13X, применяемых для осушки газа, и предложен интегрированный маршрут переработки. Предлагаемый маршрут включает идентификацию и сортировку исходного материала, удаление мелких частиц, аналитическую диагностику, низкотемпературную сушку, термическую десорбцию, контролируемое окислительное удаление углеродистых остатков в обоснованных случаях, охлаждение в среде сухого газа, классификацию по фракциям, испытание водоадсорбционной способности и механический контроль качества. В зависимости от восстановленных эксплуатационных характеристик регенерированный материал может быть возвращён в процесс осушки, направлен на менее требовательные адсорбционные процессы или преобразован во вторичное алюмосиликатное сырьё. Статья основана на анализе литературных данных и не содержит результатов оригинальных промышленных испытаний; поэтому температурные диапазоны и критерии приемки представлены как предварительные диапазоны для скрининговой оценки, которые должны быть подтверждены для конкретного коммерческого цеолита, связующего и профиля загрязнений.*

Ключевые слова: *осушка природного газа; молекулярное сито; цеолит; отработанный адсорбент; регенерация; переработка; термическая обработка; удаление кокса; циркулярная экономика.*

Highlights

- Spent gas-dehydration molecular sieves should be diagnosed before regeneration because deactivation mechanisms are not identical.
- Methanol and hydrocarbon contamination can produce persistent carbonaceous residues and substantial water-capacity loss.
- Excessively severe regeneration can accelerate structural aging; temperature must therefore be optimized rather than maximized.
- A staged reprocessing scheme combining desorption, controlled decoking and post-treatment qualification is proposed.
- Recovered adsorbent should be routed according to measured adsorption capacity and mechanical integrity, not visual appearance alone.

1. Introduction

Removal of water vapor is a critical step in natural-gas processing. Water promotes corrosion in the presence of acid gases, contributes to gas-hydrate formation at high pressure and low temperature, and can freeze or interfere with cryogenic and downstream separation equipment. Solid-desiccant dehydration is especially important when very low water concentrations or low dew points are required. Among commercial solid desiccants, zeolite molecular sieves are distinguished by strong water affinity, selective micropores and high thermal stability, and LTA-type molecular sieves such as 3A and 4A are widely used in gas-processing service [1-4].

Industrial molecular-sieve beds are operated cyclically, usually by temperature-swing adsorption (TSA). One bed adsorbs water while another is regenerated with heated gas and then cooled before returning to adsorption duty. In an ideal cycle only reversibly adsorbed water is removed. In real plants, however, the sieve is exposed to repeated heating and cooling, contaminants in the gas stream, upstream carryover and mechanical stresses. These factors may progressively reduce water uptake and shorten breakthrough time. Recent studies show that adsorbent aging is not a minor secondary issue but a defining factor in dehydration-unit performance [4,5].

A common operational response is complete replacement of the adsorbent bed. This approach restores drying capacity but transfers the problem to waste management and increases replacement cost. The central assumption of the present article is different: spent molecular sieve should first be treated as a potentially recoverable process material. The key question is not whether every spent pellet can be returned to its original duty, but which fraction can be regenerated safely, how much capacity can be restored, and what secondary use is technically justified for the remaining fraction. This requires a diagnostic and decision-based reprocessing technology rather than a single universal heating procedure.

The objective of this work is to analyze the main mechanisms responsible for degradation of zeolites used in gas dehydration, compare available regeneration approaches, and formulate an integrated technology for reprocessing spent molecular sieves. The article follows the format of a review and conceptual technological assessment. No original industrial performance data are reported; proposed operating windows must therefore be confirmed experimentally before scale-up.

2. Methodology of the Review and Technological Assessment

The assessment was developed from recent peer-reviewed literature on natural-gas dehydration, molecular-sieve aging, contaminant exposure, thermal cycling and regeneration of deactivated zeolites. Particular attention was given to industrial LTA and FAU materials and to studies published from 2018 to 2026. Earlier references were used only where they provide basic engineering context. The evaluation criteria were: (i) ability to remove reversibly adsorbed water; (ii) ability to remove organic or carbonaceous deposits; (iii) preservation of zeolite crystallinity and pore structure; (iv) mechanical integrity of shaped pellets; (v) energy and gas demand; (vi) process safety and controllability; and (vii) feasibility of subsequent reuse or material recovery.

The literature demonstrates that the same spent molecular sieve can contain several forms of deactivation simultaneously. For this reason, regeneration technologies were not ranked by maximum temperature alone. Instead, the proposed process uses diagnosis to select the minimum treatment severity necessary to remove the dominant contaminant while limiting additional thermal or hydrothermal damage.

3. Zeolites Used in Gas Dehydration and Their Deactivation

3.1. Functional role of molecular sieves

Zeolites are crystalline aluminosilicates containing molecular-scale pores and exchangeable cations. Their hydrophilicity originates from framework aluminum and associated charge-compensating cations, which create strong electrostatic interactions with water. Commercial gas-dehydration products are generally shaped as beads or extrudates and may contain approximately 10-20 wt.% binder, depending on product formulation. LTA zeolites are widely used for water removal, while 13X (FAU topology) can offer higher pore volume but also admits larger molecules. Molecular-sieve selection therefore reflects both the target water specification and the risk of co-adsorbing hydrocarbons or other contaminants [1,6].

3.2. Major deactivation mechanisms

Spent adsorbent performance is controlled by a combination of reversible loading and irreversible or partly irreversible aging. The most important mechanisms are summarized in Table 1. Reversible water loading should be removed during normal regeneration. More persistent capacity loss is associated with carbonaceous residues, pore blockage, chemical contamination, structural changes and attrition. A 2022 study of 4A, 5A and 13X molecular sieves exposed to methanol and heptane showed that methanol could cause particularly severe loss of water-vapor adsorption capacity; water uptake in methanol-exposed samples was about 50% below that of fresh zeolites, with nonvolatile residual hydrocarbons identified as an important cause [2].

Hydrocarbon exposure is also important. Accelerated aging experiments simulating TSA operation found n-heptane to be a major factor promoting zeolite aging under the tested conditions [3]. In addition, repeated temperature cycling can itself alter adsorbent performance. Jacobs et al. reported that long-term cycling degradation depended strongly on regeneration temperature. For 13X, capacity loss after 5,000 cycles increased as the tested regeneration temperature rose, whereas 4A was considerably more stable under the same high-temperature cycling experiment [4]. The result does not imply that one universal temperature is optimal; it shows that regeneration severity must be matched to material type and service history.

Table 1. Main causes of spent molecular-sieve deactivation in gas dehydration.

Deactivation mechanism	Typical origin	Diagnostic indicators	Reprocessing implication
Residual water loading	Incomplete normal regeneration, poor heat distribution	High mass loss at low/intermediate temperature; low initial capacity	Dry-gas thermal desorption may be sufficient
Hydrocarbon / methanol-derived deposits	Feed carryover, methanol injection, condensable hydrocarbons	CHNS/TGA carbon signal; darkening; reduced micropore uptake	May require controlled oxidative decoking after inert desorption
Pore blockage by oil or heavy organics	Compressor oil, glycol, condensate, heavy hydrocarbon carryover	High extractables; FTIR organic bands; low BET/micropore volume	Pre-cleaning or staged thermal treatment; severe cases may be rejected

Hydrothermal / thermal aging	Repeated TSA cycles, excessive regeneration severity	Reduced crystallinity or altered adsorption kinetics	Avoid unnecessary high temperature; verify XRD and water capacity
Binder damage and attrition	Thermal stress, pressure drop, handling	Fines generation, reduced crush strength	Screen out fines; mechanically weak pellets should not return to primary bed
Inorganic contamination	Corrosion products, salts, particulates	XRF/SEM-EDS changes; ash increase	Physical separation or secondary use may be more rational than reactivation

4. Current Approaches to Regeneration and Reprocessing

4.1. Thermal desorption with dry gas

Thermal desorption is the basic regeneration mechanism for water-loaded molecular sieves. Heating lowers the equilibrium loading and releases strongly adsorbed water, while a dry purge removes desorbed vapor from the bed. Published engineering literature commonly places complete water desorption from zeolites in a high-temperature range, and cyclic industrial practice typically uses a controlled heating, soak and cooling sequence rather than abrupt heating [1,2]. For spent adsorbent reprocessing, however, the purpose differs from routine bed regeneration: the goal is to recover capacity without adding new thermal damage. Therefore, a screening program should begin with the mildest temperature capable of removing water and volatile contaminants.

4.2. Controlled thermal oxidation for carbonaceous deposits

When TGA, CHNS, FTIR or other analyses confirm persistent organic or carbonaceous residues, inert thermal desorption alone may not restore micropore accessibility. Controlled oxidation can remove coke-like deposits, but the treatment window must remain below the temperature at which the zeolite framework or binder loses integrity. A 2025 study of 3A molecular sieves removed from a gas refinery after four years of service found that heating could regenerate deactivated material and that the zeolite structure remained essentially unchanged up to approximately 550 degrees C; significant structural change occurred at higher temperatures. Even after regeneration in the investigated 400-550 degrees C range, water capacity remained about 40% lower than fresh material, showing that decoking can recover performance without necessarily restoring the virgin state [7].

For aged industrial 4A molecular sieves, a 2025 study also reported improvement of dehydration capacity after heat treatment under oxygen-enriched air [8]. These results support a controlled oxidative step for selected spent batches, but they do not justify direct air calcination at the maximum temperature. Local hot spots, exothermic coke combustion and binder sensitivity must be considered. A practical technology should therefore use staged oxygen introduction and temperature monitoring after the volatile fraction has first been removed under inert or low-oxygen conditions.

4.3. Chemical washing and solvent extraction

Chemical or solvent washing can in principle remove oils, glycols, salts or other surface contaminants. Nevertheless, zeolite molecular sieves are ion-exchange materials, and aggressive acids, bases or high-water washing conditions can alter cation form, framework aluminum, binder properties and pellet strength. Chemical washing should therefore not be treated as a universal first step. It is most defensible when the contaminant has been identified and a compatibility test confirms that the washing agent does not reduce crystallinity, water capacity or mechanical strength. For hydrocarbon-dominated contamination, thermal separation is generally simpler to integrate with gas-plant practice.

4.4. Mechanical classification and secondary material routes

A meaningful fraction of removed molecular sieve may be physically damaged rather than chemically exhausted. Fines and broken pellets increase pressure drop and are unsuitable for return to a primary dehydration vessel, even if their intrinsic adsorption capacity remains high. Screening should therefore be an explicit reprocessing stage. Material that fails mechanical acceptance but retains aluminosilicate structure can be evaluated for less demanding adsorptive duties or as an aluminosilicate feedstock. General spent-adsorbent literature emphasizes a hierarchy of regeneration for reuse, secondary functional use and, only when necessary, safe disposal [9].

Table 2. Comparative assessment of regeneration options for spent gas-dehydration zeolites.

Method	Best-suited contamination	Main benefit	Main limitation / risk	Recommended role
Dry-gas thermal desorption	Water and volatile organics	Simple, compatible with TSA practice	May not remove coke-like residues	First regeneration stage

Controlled oxidative thermal treatment	Coke / persistent carbonaceous deposits	Restores blocked pore volume	Exotherm, framework and binder damage at excessive severity	Conditional second stage after diagnosis
Solvent washing	Oil, glycol or selected organics	Targets extractable contamination	Solvent recovery; possible pellet/binder effects	Case-specific pre-treatment
Acid/base washing	Selected inorganic contaminants	Can dissolve salts or deposits	May alter zeolite chemistry and ion-exchange state	Not a default route; use only after compatibility testing
Screening / air classification	Fines and broken pellets	Improves hydraulic/mechanical quality	Does not restore adsorption capacity	Mandatory physical conditioning
Material recovery / secondary use	Adsorbent that cannot meet primary-bed specification	Reduces disposal and preserves material value	Requires contaminant and application-specific qualification	Final route for non-primary-grade material

5. Proposed Integrated Technology for Reprocessing Spent Zeolite

The proposed technology is based on a decision tree rather than a fixed one-temperature treatment. Each batch is first identified by zeolite type, supplier or product grade, years of service, bed position and known process upsets. Mixing unknown 3A, 4A, 5A and 13X wastes before characterization should be avoided because pore size, cation form, binder and thermal behavior differ. The integrated sequence is shown in Figure 1.



Figure 1. Proposed integrated route for reprocessing spent zeolite molecular sieves from gas-dehydration service.

5.1. Stage 1 - receipt, segregation and safe conditioning

Spent adsorbent should be transferred in closed containers where practical and accompanied by process-history information. The first technical decision is whether the material has been exposed to hazardous compounds that would constrain reuse or thermal treatment. Representative samples are taken from each batch. Oversize foreign matter and excessive fines are removed by sieving. The mass fraction of fines is recorded because it is an indirect indicator of attrition and bed deterioration.

5.2. Stage 2 - diagnostic characterization

The minimum recommended diagnostic package is: moisture/volatile loss, TGA/DTG, XRD, FTIR, CHNS or total carbon, water adsorption capacity, particle-size distribution and crush-strength or attrition testing. BET or micropore analysis, XRF and SEM-EDS are added when available. Comparison with an unused reference sample from the same product grade is strongly preferred. This stage prevents two costly errors: over-treating material whose main problem is reversible loading, and attempting to regenerate material whose framework or mechanical integrity has already failed.

5.3. Stage 3 - low-temperature drying and inert desorption

A preliminary drying/desorption step should remove free moisture, weakly adsorbed water and volatile hydrocarbons before any oxidative treatment. For laboratory development, a staged screening range of approximately 105-150 degrees C for initial drying followed by 200-320 degrees C under dry inert or oxygen-lean purge can be evaluated. These values are not universal plant set points; they are a rational experimental window that brackets water desorption while remaining less severe than high-temperature decoking. Mass loss and off-gas composition should be monitored to determine whether volatile removal is complete.

5.4. Stage 4 - controlled decoking when required

If carbon analysis and TGA show a significant nonvolatile organic fraction after inert desorption, a controlled oxidative stage can be tested. A practical laboratory screening window is approximately 350-500 degrees C with gradual introduction of oxygen-containing gas and strict bed-temperature control. The upper limit must be material-specific. The

2025 study on spent 3A molecular sieve found structural preservation up to about 550 degrees C under its experimental conditions but deterioration at higher temperature [7]. Accordingly, 550 degrees C should be treated as an evidence-based caution boundary for that particular 3A material, not as a routine operating target for every zeolite.

5.5. Stage 5 - cooling, grading and qualification

After regeneration, the adsorbent should be cooled under dry gas to prevent immediate readsorption of atmospheric moisture. The regenerated material is then screened again to remove newly generated fines and subjected to water-capacity and mechanical testing. The decisive parameter is not color change but restored function. For process development, a restoration coefficient can be defined as Kq = qreg/qfresh x 100%, where qreg is the equilibrium or standardized dynamic water capacity of the regenerated sample and qfresh is the corresponding value for fresh product. A mechanical retention coefficient can similarly be defined from crush strength or attrition data. Acceptance limits must be set by the plant, equipment design and product specification.

Table 3. Suggested laboratory screening matrix for technology development (not universal operating specifications).

Stage	Purpose	Variables to screen	Primary control	Decision
Feed characterization	Identify deactivation mechanism	Bed position, service time, contaminant history	XRD, FTIR, TGA/DTG, CHNS, water capacity, crush strength	Select treatment route
Initial drying	Remove free/weakly bound moisture	Approx. 105-150 degrees C; time; purge flow	Mass loss, outlet humidity	Proceed when moisture stabilizes
Thermal desorption	Remove strongly adsorbed water/volatiles	Approx. 200-320 degrees C; heating rate; purge gas	TGA correlation, off-gas, water capacity	Stop if capacity is adequately restored
Controlled oxidation	Remove persistent carbonaceous deposits	Approx. 350-500 degrees C; oxygen concentration; residence time	Bed temperature, CO/CO2, residual carbon, XRD	Optimize minimum severity
Cooling	Prevent readsorption and thermal shock	Dry-gas cooling rate	Outlet temperature/dew point	Ready for testing
Qualification	Determine reuse route	Capacity, kinetics, crush strength, attrition, fines	Kq and mechanical retention	Primary reuse / secondary use / reject

6. Qualification Criteria and Reuse Strategy

A regenerated batch should not automatically return to the original dryer. Qualification should compare fresh, spent and regenerated samples using the same protocol. At minimum, the comparison should include equilibrium or standardized water uptake, dynamic breakthrough behavior, adsorption/desorption kinetics and mechanical integrity. XRD alone is insufficient: a sample can remain crystalline while losing meaningful water capacity because of pore blockage or binder-related effects [2].

For pilot development, the following routing concept is recommended. Material that recovers close to fresh adsorption performance and passes mechanical tests can be considered for blending trials or controlled return to dehydration service. Material with moderate capacity recovery but acceptable strength can be tested in less demanding pre-drying or guard-bed service. Material that is structurally intact but mechanically unsuitable may be ground and evaluated as a secondary aluminosilicate adsorbent or raw material, subject to contaminant assessment. Material with hazardous contamination, irreversible structural collapse or unacceptable leaching behavior should be directed to regulated disposal. Numerical acceptance thresholds should be established from plant specifications and pilot data rather than copied generically between facilities.

Table 4. Decision matrix for regenerated zeolite routing.

Measured condition after treatment	Interpretation	Preferred route
High water-capacity recovery + acceptable kinetics + acceptable strength	Functional adsorbent largely restored	Pilot return to gas-dehydration service or blending with fresh sieve
Moderate capacity recovery + good mechanical integrity	Adsorbent still functional but may not meet deep-drying duty	Secondary drying, guard-bed or less stringent adsorption service

Low adsorption recovery + retained aluminosilicate structure	Micropore function substantially impaired	Material recovery / alternative adsorbent or mineral raw-material research
Severe framework loss, high attrition or hazardous contamination	Regeneration is technically or environmentally unjustified	Controlled disposal according to waste classification

7. Mechanistic Basis of the Proposed Technology

The logic of the process can be understood by separating reversible adsorption from irreversible obstruction. Water molecules are strongly attracted to zeolite cations and framework oxygen; heat and a dry purge shift the adsorption equilibrium and remove them. Hydrocarbon-derived deposits behave differently. They may occupy pore volume, cover adsorption sites or create diffusion barriers. The molecular-simulation analysis reported for deactivated 3A material showed that coke in zeolite cavities reduces the interaction energy between water and the zeolite, consistent with lower water uptake [7]. Removing the deposit can therefore restore part of the effective adsorption volume.

At the same time, regeneration itself can become a source of degradation. Long-term cycling data show a temperature-dependent loss of adsorption capacity, particularly for 13X under severe repeated thermal treatment [4]. A separate 2023 study examining CO2 and water effects over many cycles also demonstrated that process-fluid composition can influence degradation behavior [10]. Thus, the correct engineering objective is not maximum coke burnoff at maximum temperature; it is maximum useful capacity recovery at the lowest severity that preserves structure and mechanical strength.

8. Environmental and Techno-Economic Considerations

Reprocessing can reduce the volume of solid adsorbent sent to disposal and can defer purchase of replacement molecular sieve. The benefit, however, depends on energy consumption, purge-gas demand, off-gas treatment, yield of mechanically acceptable product and the number of additional service cycles obtained. A proper techno-economic study should therefore report at least: mass yield of reusable pellets, restored water capacity, regeneration energy per kilogram of accepted product, purge-gas consumption, off-gas treatment requirement, fraction routed to secondary use, and avoided disposal and replacement cost.

Environmental assessment must also consider the fate of removed contaminants. Oxidative decoking converts organic residues to gaseous products and may generate CO, CO2 and volatile compounds that require controlled exhaust handling. Solvent washing transfers contaminants to a liquid waste stream and therefore should only be used when solvent recovery and wastewater management are justified. The circular economy advantage of regeneration is real only when the secondary emissions and residues are included in the system boundary [9].

9. Research Gaps and Experimental Program

The principal research gap is the limited amount of public data on spent molecular sieves removed from real gas-processing plants. Aging is strongly dependent on gas composition, upstream separation quality, methanol or glycol carryover, regeneration history, bed temperature profile and adsorbent formulation. Recent work on industrial 4A samples taken from different levels of a dehydration column shows the value of spatially resolved sampling because residual properties can vary with bed position [8].

A defensible experimental program should therefore compare samples from the top, middle and bottom of the actual industrial bed. The recommended sequence is: (i) baseline characterization of fresh and spent zeolite; (ii) mild thermal-desorption screening; (iii) controlled oxidative regeneration only for samples with persistent carbonaceous residues; (iv) optimization by water-capacity recovery and mechanical retention, not by carbon removal alone; (v) repeated adsorption-regeneration cycles on the recovered adsorbent; (vi) dynamic breakthrough testing with representative wet gas; and (vii) pilot-scale pressure-drop and attrition evaluation. This would convert the present conceptual route into an original research article with plant-specific performance and economic data.

10. Conclusion

Spent zeolite molecular sieves from gas-dehydration units should not automatically be considered irrecoverable waste. Recent literature shows that the dominant causes of performance loss include methanol- and hydrocarbon-derived deposits, coking, repeated thermal cycling, pore blockage, binder deterioration and mechanical attrition. At the same time, published regeneration studies demonstrate that controlled heat treatment can recover part of the dehydration capacity of aged 3A and 4A molecular sieves. The critical limitation is that severe heating can also accelerate irreversible degradation, and complete restoration to fresh-sieve performance is not guaranteed.

The most rational reprocessing technology is therefore a staged diagnostic route: segregation and screening; physicochemical diagnosis; mild drying and inert desorption; controlled oxidative decoking only when justified; dry-gas cooling; mechanical classification; and performance qualification. Reuse decisions should be based on measured water

adsorption, breakthrough behavior and mechanical strength. This approach can create three value streams - regenerated adsorbent for primary service, lower-grade adsorbent for secondary service, and aluminosilicate material for further recovery - while minimizing the fraction that requires disposal. Plant-specific laboratory and pilot validation remains essential before industrial implementation.

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Note: Author names, affiliations and plant-specific experimental data should be inserted before journal submission.