TENORM and ALARA in the Florida Phosphate Industry

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1. Abstract

This paper explores two coupled issues: first, results of research into key aspects of TENORM and ALARA in the Florida Phosphate Industry; secondly, the extent to which conclusions from that research may bear on the challenge of managing the vast quantities of phosphogypsum that result from phosphoric acid production as a potential asset rather than a hazardous waste.

The Florida Institute of Phosphate Research (FIPR) has conducted research on exposures to technologically enhanced naturally occurring radioactive materials (TENORM) for 25 years. Specifically, FIPR has studied the energy spectrum of the TENORM working environment, external doses, radon concentrations and working levels, and inhalation of airborne particulate matter. Recent research has concentrated on the inhalation dose component by using cascade-impactor sampling and lung fluid dissolution studies. Available results of these studies are presented as compared to federal and state standards, and practical recommendations are made to keep radiation doses ALARA.

Since 1992, the US Environmental Protection Agency (EPA) “Rule” regarding phosphogypsum has heavily restricted its use, based on radium content and primarily the potential for increased public exposure to radon. Thirteen years on, some measure of the impact of the Rule can be made, a process, which FIPR is supporting through co-funding a research study into potentially safe, beneficial uses of phosphogypsum. As well as the operational and commercial considerations that will need to be satisfied if such uses are to be found and permitted, there are doubts to be resolved concerning the theoretical basis on which the risk assessment procedures that underpin the Rule rests, and in particular whether the Rule itself runs contrary to the ALARA principle.

2. The context

Florida currently supplies 75% of U.S. and 25% of the world’s phosphate demand. The Florida phosphate industry began in the late 1880s; now it directly employs over 6,000 workers and more than 30,000 indirectly, most concentrated in the belt between Tampa and Bartow along State Road 60. This once isolated area is now

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home to a rapidly growing population of some 2 million people. It makes an excellent location to study a variety of TENORM and ALARA issues, in the workplace, the wider community and the environment.

Since 1992, the USEPA and other regulatory agencies around the world have restricted, or banned, the use of phosphogypsum based on radium content and primarily the potential for increased public exposure to radon. Thirteen years into this regulatory regime, it is possible to make a preliminary review of its impact in respect of public and environmental health, both longitudinally in respect of its cumulative effect, but also in regard to the critical control points for protecting industry workers and the wider public from any acute risks. A project of global significance, under the direction of AleffGroup, Inc., was recently co-funded by FIPR, to initiate such a review. It is exploring the theoretical and methodological underpinnings of the regulations, but also is investigating from a practical and commercial point of view potentially acceptable alternatives to the regime of “stacking” phosphogypsum. This presentation explores a pivotal aspect of the review: whether segregation of phosphogypsum by stacking is the best option. May the overall public and environmental benefit of using phosphogypsum make the cost to avoid little or no additional radiation dose an unreasonable expenditure; is the “zero tolerance” approach to stacking phosphogypsum contrary to the ALARA philosophy?

The wider research project to which it contributes may in time have a profound impact on workplace practices, environmental stewardship, and policy decisions in respect of the worldwide generation, disposal, storage and use of phosphogypsum, including agreeing potentially safe, beneficial uses.

3. The phosphate industry and TENORM

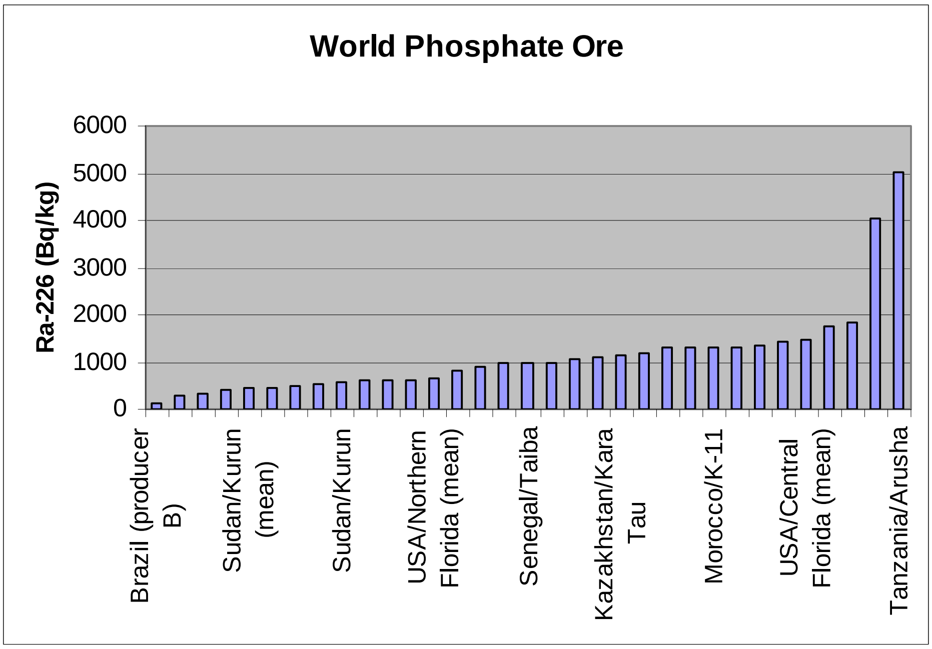

Figure 1. Average Ra-226 activity concentrations in phosphate deposits worldwide.

As a point of reference, central Florida deposits average 1460 Bq/kg (Birky *et al*., 1998). Furthermore, these radionuclides may become technologically enhanced, i.e., their activity concentrations may increase during industrial processing.

Naturally occurring radioactive materials (NORM) are associated with phosphate deposits throughout the world. However, activity concentrations of the individual radionuclides vary markedly (Figure 1). For example, activity concentrations of Ra-226 in phosphate ore range from a little over 100 to thousands of Bq/kg (Birky, 2002).

3.1 Mining and beneficiation

In central Florida, sedimentary phosphate rock is found in a matrix of roughly equal parts of phosphate rock, sand, and clay. After the matrix is removed from the ground by strip mining, the mining companies need to separate the phosphate rock from the sand and clay. This process is called “beneficiation”. The beneficiation process is largely mechanical in nature. First, the “feed” material, matrix slurry, is separated by mesh size. Sized flotation feed is dewatered and conditioned with a fatty acid/fuel oil mixture. The phosphate is then floated to produce a rougher concentrate and a sand tailing. The rougher concentrate goes through a dewatering cyclone, an acid scrubber, and a wash box to remove the reagents from the phosphate surfaces. After rinsing, the deoiled rougher concentrate is transported into flotation cells where amine is added. The silica is finally floated at neutral pH.

Of all NORM radionuclides, U-238 and Ra-226 are by far the most frequently reported in literature. After the beneficiation process, clay and phosphate rock can be slightly enhanced compared to the matrix, but these numbers are essentially the same. However, the sands are *depleted* in radioactivity, and are very similar in concentrations to central Florida mineralised topsoil. Consequently, no significant technological enhancement takes place during mining and beneficiation.

3.2 Chemical processing and fertiliser production

Only after the phosphate rock is transported to the chemical processing plant, where phosphoric acid and concentrated fertilisers are manufactured, does the only significant chemical enhancement process take place. The rock slurry is ground in ball mills and reacted with sulphuric acid to make phosphoric acid. At the same time, phosphogypsum (mainly calcium sulphate) is made. Chemically speaking, almost all of the uranium is in the phosphoric acid and most of the radium is in the phosphogypsum. The phosphoric acid and phosphogypsum are still mixed in the reaction vessel and must be mechanically separated using filtration equipment. The most widely used filtration apparatus is the rotating pan assembly (Bird design).

Once separated, the acid and phosphogypsum have the approximate concentrations shown in Table 1 (Adapted from Birky *et al*., 1998). Note that the phosphogypsum is depleted in radioactivity compared to the matrix and phosphate rock naturally found in the ground.

Table 1. Ra-226 and U-238 distributions in the central Florida phosphate industry.

NORM Distribution (Bq/kg)			
Ra-226	**U-238**	**Material**	**Process Stage**
1400	1400	Matrix	Mining
1430	1610	Clays	
230	200	Sand	Beneficiation
1460	1350	Rock Concentrate	
1100	<40	Gypsum	Chemical Processing
<40	1100	Phosphoric Acid	
170	2560	MAP/DAP	Fertiliser Products
>>1400	420	Scale	Waste

The phosphoric acid is used to make granulated concentrated fertilisers: monoammonium phosphate (MAP), diammonium phosphate (DAP), granulated triple superphosphate, and animal feeds. The most significant commodity in terms of volume produced and sales is DAP. DAP is enhanced in uranium compared to the original rock, but it is greatly diluted when the final blended fertilisers for field applications are made.

Radium has a tendency to deposit and build up as scale on some pipes and vessels. Some of the scale can accumulate to very high concentrations, even several hundred thousand Bq/kg. The result of the scale build-up is that exposure rate readings near these objects climbs into the mR/hour range and employees are advised not to linger nearby. When taken out of service, these objects, or just the scale they contain, are discarded according to procedures established in the company's radioactive materials license with the government. In the U.S., scale is commonly discarded in cells within the phosphogypsum stacks.

4. FIPR research

Over the past 25 years, FIPR had conducted many studies on NORM and TENORM in the phosphate industry and the surrounding environment. A few studies of relevance to occupational ALARA are described in the following sections.

4.1 The NORM/ TENORM energy spectrum

Hand-held survey instruments are sometimes used to assess exposures to personnel or potential exposures to the public. The most common categories of survey instruments used in the phosphate industry are the solid scintillation (sodium iodide crystal) design and the gas-filled chamber design. These instruments are not very accurate when used to measure low-energy gamma radiation as is typical of environmental settings. A FIPR study (Weger *et al*., 2004) evaluated the most common makes and models of survey instruments used in the phosphate industry in comparison to a broad energy germanium gamma spectrometer. This instrument is capable of quantifying gamma emissions by energy. The vast majority of photons collected in phosphate industry settings had energies of less than 500 keV. In this energy range, the Ludlum survey meters are known to drastically over-respond and indicate a higher than actual exposure rate.

Conversion factors to determine actual exposure from survey meter readings (Ludlum models 12-S and 2401-P) were calculated using the measured energy spectra and the energy-dependent response curves of the survey meters. Dose conversion factors (Roentgen-to-rem) were then calculated using the energy spectra and the energy-dependent data published by the International Committee on Radiological Protection (ICRP) for six orientations of external exposure. The study shows that the true dose rate (microrem per hour) in the average phosphate industry TENORM setting is from 40 to 45 percent of the survey meter reading in microroentgens per hour.

What does this mean in practical terms? The dose limit to a member of the public in Florida is 100 millirem (1 mSv) per year due to man's activities above natural background dose. As an example, an off-site release policy of 50 microrem per hour above background for radioactive objects is set to keep a member of the public to under 100 millirem total exposure over 2,000 hours in the year. That is: (50 microrem/hour) x (2,000 hours) = 100,000 microrem = 100 millirem (1 mSv). In the past, a survey meter reading of 50 microroentgens per hour was considered equal to this level. This research shows that a reading of 125 microroentgens per hour using a Ludlum Model 12-S meter is actually equivalent to a dose of 50 microrem per hour. In terms of worker doses previously calculated using this same instrument: they may have been overestimated by 60 percent.

Use of these new dose conversion factors produces more accurate dose estimates to industry employees and members of the public. If the release policy is amended accordingly, more materials having value could be recycled rather than being buried in phosphogypsum stacks.

Conversion factors of measured to actual exposure for the Ludlum 12-S and 2401-P (calibrated with a ^{137}Cs source) are 0.55 ± 0.07 and 0.62 ± 0.06, respectively, averaged over the phosphate industry. The dose conversion factors of actual exposure to effective dose for the following orientations of external gamma irradiation to the body are 1.07 ± 0.04 antero-posterior, 0.89 ± 0.01 postero-anterior, 0.64 ± 0.01 right lateral, 0.69 ± 0.01 left lateral, 0.86 ± 0.02 rotational, and 0.73 ± 0.01 isotropic. Consequently, the meter reading is converted to an effective dose rate by multiplying the two appropriate conversion factors. For example, a Ludlum 12-S meter indicating 50 µR per hour in an isotropic field yields a dose rate of (0.55 x 50 µR/hr) x 0.73 µrem/µR = 20 µrem per hour.

Routine daily exposures of phosphate industry personnel to ionising radiation are measured using badge dosimeters worn on the chest and processed by dosimetry vendors. Aluminium oxide carbide and lithium fluoride dosimeters were evaluated at the filtration areas and rock storage tunnels of the phosphate chemical processing plants. Conversion factors of measured to actual dose (not including orientation of gamma radiation to the body) for the aluminium oxide dosimeter and the lithium fluoride dosimeter are 0.967 ± 0.012 and 0.918 ± 0.024, respectively, for the industry.

4.2 External radiation doses

External doses were measured in the 1998 FIPR study using lithium fluoride and aluminium oxide dosimeter badges. All doses were all very low. The industry average (geometric mean) for a worker was 0.21 mSv/a. Average annual doses (mSv/a) based on lithium fluoride dosimeters by work area were: dry products area (0.17), shipping areas (0.20), mine areas (0.17), phosphoric acid areas (0.31), rock handling areas (0.30), and off-site service areas (0.18).

4.3 Internal radiation doses

The internal dose component of the total effective dose equivalent (TEDE) is the combination of inhalation dose, ingestion dose, and the far less common introduction of radionuclides into the body through intact skin or wounds. In this setting, ingestion and wound entry doses are negligible (Birky *et al*., 1998). The inhalation dose component was measured using medium and high-volume air samplers fitted with paper filters to collect airborne particulate matter. Such a sampling technique gives only a rough and conservative estimation of the inhalation dose, because there are many parameters used in the lung dose model that are not measured and must be assigned default values. Further discussion of the effect of this inhalation dose estimation on the TEDE and methods used to measure doses in work areas targeted by this study are discussed in the next section.

Essentially all work areas in phosphate mining, beneficiation, and chemical processing facilities are open to the outside with free air exchange. The main exception is the control rooms, which are ventilated with air conditioners. Radon and radon daughter concentrations are at background levels throughout much of these facilities. The only exception is found in the rock tunnels. Phosphate rock is piled over cylindrical tunnels, open at either end. The rock is pushed through chutes to a conveyor belt within the tunnel that carries the rock to be ground in ball mills. The radon levels in rock tunnels are high, although working levels are not excessive (<1 mWL) suggesting that equilibrium factors are generally low.

4.4 TEDE

Total doses were calculated using measured results coupled with uncertainty analysis using Latin Hypercube sampling to yield distributions rather than single point doses. For most areas, the inhalation component did not add greatly to the TEDE. However, for the shipping area, including transfers from the dry products area, and some duties (e.g. reactor cleaning) there is a greater probability that the public dose limit of 1 mSv/a might be exceeded by workers who are not trained and monitored as radiation workers. The authors (Birky *et al*., 1998) pointed out that these inhalation-driven higher doses were based on conservative assumptions for parameters that could not be measured in the study. Consequently, follow-up studies were funded by FIPR and are currently in progress. In the first such study, additional breathing zone samples were collected using dichotomous and cascade impactor samplers to determine radioactivity by particle size in 7 stages, particle shapes, and particle chemistries. In addition, a parameter sensitivity analysis was conducted. Inhalation doses are calculated using the most recent version of the LUDEP code based on the ICRP lung model. It was determined that solubility of particles in lung fluid was the most influential parameter on the final dose and that portion of the study is in progress.

5. ALARA recommendations

- All external doses estimated based on survey meters should employ the dose conversion factors based on the work of Weger *et al*., 2004.

- Regulators should use the energy spectrum information and conversion factors when setting release criteria for contaminated objects.

- If it is practical to do so, dust emissions should be restricted or contained at the source. In storage areas, dry products are coated with oils to inhibit dust.

- In the absence of, or in addition to such controls, use of a respirator can offer protection against inhalation of airborne activity. For most situations in this industry, a basic mist mast with a protection factor of 10 is sufficient when properly fitted and worn.

- Regulatory decisions on changes to current respiratory protection practices should await the results of the current FIPR study of particle solubility in lung fluids and final inhalation dose estimations for the industry.

- Regulatory agencies should also consider the ICRP recommendation that in clearly identified populations, the appropriate expenditure for ALARA purposes may be as much as a few hundred dollars (U.S.) per 0.01 person-Sv avoided.

- Regarding radon, rock tunnels should be ventilated (usually by large fans), and worker occupancy times should be limited. The ventilation system can be operated in advance of planned entries so that the entire volume of air in the tunnels is replaced, and the fans should remain in operation during occupancy.

- Workers should receive training in the basic principles of radiation protection and risk commensurate with their exposures.

6. The phosphogypsum issue

Managing the ever-increasing quantities of phosphogypsum that result from phosphoric acid production is a public and environmental policy issue in which the “reasonably achievable” concept of ALARA has the potential to unlock a currently deadlocked situation. There are two key problems, one theoretical, the other practical.

At the theoretical level, the ALARA theory seems at odds with the approach that EPA takes to potential risks from phosphogypsum under the 1992 Rule. ALARA rests on a relative model of risk, in which the threshold rather than the risk is the determining point. The 1992 Rule, perhaps based on the Precautionary Principle, takes a “zero tolerance” approach to incremental risk, in which any additional exposure, even when still well within “normal” ranges, and below the threshold, is disallowed. The difference of approach is evident throughout, for example in the definitions section, which states categorically that phosphogypsum is “a waste by-product from processing phosphate rock […] of limited economic or environmental value”. This is more a judgment than definition. An immediate consequence of that judgment is that the concepts of exposure “threshold” or “reasonableness” of risk (in regard for example to potential benefit) are rendered *a priori* invalid.

In practice, the risks posed by phosphogypsum vary very widely, as there are many varieties of the substance; and the practice of using phosphogypsum as a soil amendment in peanut farming, which long predates the Rule, has continued unabated, indicating that the characterisation “waste” is not universally applicable. There is tacit recognition of this variability in the body of the Rule to the extent that a pathway to using phosphogypsum in other settings is envisaged, but under such strict conditions that to date no examples of experimental use have been executed.

Taken together, these approaches illustrate a pivotal dilemma in science-based policy making, which is whether risk is to be seen as relative or as absolute, whether perception or fact is the key determinant in policy implementation. The dilemma is not new: similar divergences of approach are evident between Aristotle’s and Plato’s models of science, and in a text many regard as the foundation of the modern scientific method. In *The Advancement of Learning* (1610), Lord Bacon strikingly describes the likely result of attempts to accommodate both views in a single policy as a “contract of error”, of a potentially fatal kind.

So if there is a theoretical objection to the path of consensus in respect of policy regarding phosphogypsum, is there a way of reframing the debate that can lead to a new approach, both in theory and in practice? Started in April 2005, under the direction of AleffGroup, Inc., a research project, “*Stack Free by ’53? - Strategic Solutions for Phosphogypsum in both the Developed and the Developing World, with Special Emphasis on Safe, Affordable Uses in Agriculture*” is seeking out such a new approach. Co-funded by FIPR, the research team will examine the worldwide generation, disposal, storage and use of phosphogypsum, with a view to defining potentially safe, beneficial uses. This research could have a profound impact on workplace practices, environmental stewardship, and policy decisions.

Inevitably, it will also explore the seemingly wide gap between regulatory supposition and operational reality in the phosphate industry, though perhaps at a time when the collective wish to find a better solution than stacking, or dumping, makes change easier to conceive than in the recent past. At the heart of the matter is the question whether the overall public and environmental benefit of phosphogypsum use makes the cost to avoid little or no additional dose an unreasonable expenditure that is contrary to the ALARA philosophy, or if segregation from the public truly is the best option.

7. Current practice

The most common practice used to segregate phosphogypsum from the public is to “stack” it on land (Figure 2). With respect to phosphogypsum storage, for example, such stacks already dominate the landscapes of central Florida and Louisiana, and some fifty other countries are known to have stacks. A typical stack, near design capacity, contains billions of litres of acidic water. Some of this water sits in large reservoirs (“ponds”) on the stack surface; the remainder resides in circulation ditches and pore spaces within the phosphogypsum. In the past, stack containment has failed due to improper stack maintenance or extreme weather conditions resulting in the release of acidic water to the environment.

Since phosphogypsum is a useful material, it is reasonable to explore the risks and benefits associated with its use so that alternatives to stacking are fully considered. Under the existing and influential US EPA rules, phosphogypsum is assumed to continue being seen primarily as a waste rather than for its potential beneficial reuse. The "waste" designation encourages the development of stacks as the status quo until future uses are accepted instead of initiating immediate uses for phosphogypsum. Unless the framework driving the management of stacks is updated, stacks are expected to continue creating their own unique environmental concerns in existing locations, and also in many newly producing locations around the globe such as Eastern Europe, India, China, the Middle East and North Africa.

Figure 2. Phosphogypsum stacked on land.

8. A road base

Consider the use of phosphogypsum as a road base material. Research has shown that there are some very tangible public benefits, i.e., decreased labour per road-mile, decreased road completion time, and substantially decreased monetary cost per road-mile. There are more benefits that may or may not be difficult to quantify. For example, since labour decreases there is a decrease in the risk of accidents and deaths due to that labour. Such risk savings may be easy to estimate based on USDOT statistics. It is also known that a phosphogypsum road base is more durable over time and that the road will exhibit less cracking and potholes for years to come. Better road conditions translate to less accidents and fatalities.

Not only that, but the environmental benefits are compelling. Phosphogypsum is plentiful, stacked, and ready to use in many locations. In Florida, that would reduce the need for mining lime rock. It would also reduce the volume of phosphogypsum in the stacks that carry a risk of failure and environmental damage. Studies have shown that there is no observable trend in the movement of phosphogypsum road base constituents, including radionuclides, into ground water. The restricting EPA scenario is that someday the road surface is stripped away, a home is built centred over the phosphogypsum road base, and individuals spending the majority of their days and lives in that home are exposed to radon and its daughters. This scenario can be avoided by placing a deed restriction on the road so that no home would be built there, and the EPA is receptive to this approach. However, in the case of Florida, another state regulatory body inhibits this procedure. It seems plausible that the overall public and environmental benefits make the cost, in the form of regulatory restrictions and stacking, to avoid little or no additional dose to be an unreasonable expenditure.

9. Landfills

In the case of PG use as a daily cover material for municipal landfills, preliminary testing has indicated that the rate of decomposition and compaction of waste could be dramatically improved. If these results are verified by further testing, the capacity of a landfill using PG could be doubled, which would also increase the useful life of the landfill. In addition, there would be no need to dig borrow pits to provide the cover material. Since the landfill is not inhabited and is lined to prevent liquids from contaminating ground water, there is little possibility for public exposure. To the contrary, there is concern about hydrogen sulphide gas generation as an odour issue. Gas collection systems can handle this problem, and in the future, it may be desirable to harvest the gas to produce hydrogen and sulphur. Again, the limiting scenario would be radon gas generation and home construction over the landfill. This could only happen if there is loss of all institutional control. Clearly, this is another case in which the overall public benefit could outweigh the risks.

10. Agriculture

A third use of phosphogypsum, and probably the one with the most potential for reducing and nearly eliminating stacks, is as an agricultural amendment. Agricultural use is the main focus of the “Stack Free” study. phosphogypsum may offer agronomic benefit as an amendment for improving soil fertility and supplying sulphur and calcium as well as a small amount of phosphorus in both the developed and developing worlds. There is also a potential use of phosphogypsum to be investigated as an emergency remediation tool for dealing with severely nutrient depleted soils, or soils damaged by natural disasters (such as Haiti September 2004, the Indian Ocean tsunami of December 26, 2004, and the recent devastation to the United States gulf coast by Hurricane Katrina).

11. The “Stack Free” project

The “Stack Free” project itself consists of 8 interwoven work packages to be conducted over 6 years, with a break point after year 2. The global position will be studied in greater detail by means of a sector-wide survey coupled with literature review. The technical feasibility of modifying the production process will be considered from both “upstream” and “downstream” perspectives.

A reverse engineering methodology will be applied to the specification on an acceptable phosphogypsum-based soil amendment, to test the “in principle” feasibility of a solution based on use, not stacking. A market study will determine the prospects for the industry in regard to a commercially sustainable outcome. A pivotal activity is the development of reference data for the safe and efficacious use of phosphogypsum in soil amendment and crop or forage production. The end goal is to define whether or not a safe, cost-effective, high volume use of phosphogypsum can be found, especially in agriculture as a soil amendment. Research is to be conducted in the US, UK and at field centres in a range of participating countries worldwide, led and managed by an international committee of highly experienced, widely published scientists and analysts, chosen to reflect a balanced, multidisciplinary approach to the problem.

Of particular interest, in view of regulatory sensitivity concerning the radioactivity of phosphogypsum will be the measurement of its impact on the naturally occurring radioactivity of soils and the crops grown on them. Reference dose and use regimens, based on contemporary data, will be proposed and validated in field studies, for use of phosphogypsum on a range of crops, including pasture, in a range of climates and soils. Remote participation in the research process, and publication of interim and final results, will be facilitated by a part closed, part open website.

11.1 The “Stack Free” survey

The six-year Aleff Group work overlaps with the existing plan of the International Fertiliser Association (IFA) NORM task force to survey members on radiation-related issues and legislative trends. There is a clear need to develop a better understanding of potential problem areas experienced by member companies - and to share that information with regulators, consumers and other stakeholders (e.g. IAEA, insurers, developing countries) to ensure they are properly informed. This can be accomplished by: (1) technically and scientifically quantifying the associated radiation/safety risks; and (2) clarifying the “perceived risk” by providing decision-makers, regulators, and the wider public with contemporary information and data on the true risk/benefit associated with the safe management of phosphogypsum.

This is the first stage of a survey of IFA members concerning radiation safety and the handling of NORM and TENORM. In Stage 1, we are building a picture of member needs and concerns, focused on such aspects as legislation/ regulation, occupational health and product stewardship. Based on the results we get back from Stage 1, in Stage 2 we will develop a more detailed questionnaire, with a view to assisting in policy formation and the promotion of best practices. The result of the work will:

- Establish an authoritative database by country and by region of regulations and laws affecting the industry, and the extent to which such laws impact on commerce and trade;

- Evaluate potentially beneficial uses of phosphogypsum in construction and agriculture, including the use of phosphogypsum as a source of nutrients;

- Provide new information to policymakers on the safety aspects of NORM and phosphogypsum.

11.2 Sampling and analysis

Even though there are extensive data regarding phosphogypsum, the current body of information is not standardised. Much of the current published data on the radionuclide and metals contents of worldwide phosphate rock, wet acid process products, and phosphogypsum are highly variable in time of sampling, analysis methods, and parameters chosen for analysis. At best, the existing data can yield only a partial picture of the current international situation. In this addendum to the survey, we propose to request samples of rock from currently active mining sites, samples of the various products and appropriately obtained samples from active processing sites. Rock samples will be correlated to the processing sites where they are used.

For the first time, all major global rock production and processing sites will be analysed for a comprehensive set of radionuclides, metals, and other parameters of interest according to a rigorous set of protocols. In this way, the data set will be complete and uncertainties stemming from differences in analytical techniques and sample handling will be avoided. All laboratories will use the same set of handling protocols and analysis techniques. Quality Assurance/Quality Control will be maintained using chain of custody, and cross checking with standards and a statistically reliable subset of samples. Both the database and the analytical protocols used in its development will become the new benchmark for the twenty-first Century global phosphate industry.

11.3 Pathway analysis

A large body of data is available for naturally occurring radionuclides and heavy metals: their accumulation in soil, bioavailability, transfer to plants and grazing animals, and uptake by humans. Controlled studies will be conducted at Rothamsted Research, UK as needed. Once these data are evaluated and expanded with this study, it will be possible to compare the full risks incurred to the benefits of increased food production and decreased discharge of phosphogypsum and acidic water to the environment.

11.4 Justification and optimisation

In summary, it is difficult to refute that any increase in exposure to and dose from radioactive materials will result in an increase in risk to someone somewhere. However, if the health risks from radiation are surpassed by decreasing societal health risks from other causes, and economic considerations for both industry and the public are favourable, then although the radiation doses have not been kept as low as *possible*, doses are as low as *practical* and optimisation is achieved.

12. References

Alcordo I.S., Rechcigl J.E. Phosphogypsum in agriculture: A review. Advan. Agron. 1993; 49:55-118.

Birky B. 2002. Radiation Issues Associated With Phosphogypsum Use – An International Perspective. Global Gypsum Conference 2002. Miami, FL.

Birky B, Tolaymat T, Warren B, Bolch W., Ammons R, McNally T, and Nall, J. 1998. Evaluation of Exposure to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in the Phosphate Industry. Florida Institute of Phosphate Research (FIPR) Publication Number 05-046-155.

Weger H, Srivastava R, and Ebadian M. 2004. Measurement of the Energy Spectrum of Gamma-Emitting Radionuclides in Work Areas to Determine Rem per Roentgen Dose Conversion Factors for the Phosphate Industry. Florida Institute of Phosphate Research (FIPR) Publication Number 02-05-063.

Disposal management system for utilisation of industrial phosphogypsum and fly ash, European Commission Project No.: LIFE98ENV/FIN/000566; Duration: 1.7.1998 – 30.6.2002, Design Guide: Road Construction Based on Phosphogypsum and Fly Ash.