Electrostatic Separation of Plastic Materials Recycled from End of Life Vehicles

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The study was conducted on a powdery mixture derived from mechanical processing of plastics recovered from the instrument panels of ELVs, which contain varying amounts of polypropylene (PP), acrylonitrile butadiene styrene (ABS), polycarbonate (PC),cardboard, rubber, and other materials. The mixture was deposited on a metallic belt-type electrode that introduced them into an area of high intensity electric field created by a rotating cylindrical electrode, connected to a high voltage supply. This electrostatic separation method in association with classical waste processing techniques is a viable solution for the ELVs recycling industry.

Keywords: plastic waste, electric fields, electrostatic measurements, electrostatic processes, electrostatic separation

The ever increasing number of vehicles imposes the recycling issue as an extremely important problem worldwide [1, 2]. The more and stricter environmental protection regulations adopted by the European Union, for instance, requires the recycling of 95 % of the mass of the materials contained in ELVs [3, 4]. To achieve this goal, in addition to recovering the ferrous and non-ferrous metals, it is necessary to find effective solutions for the recycling of plastics, which can represent 15 – 20 % of the total weight of the ELVs. After the usual mechanical processing techniques employed for the recycling of this waste, a relative large part of it is converted into a powdery mixture of various plastics, textiles, cardboard, rubber, etc. Due to their small size (0.1 - 1 mm) these materials are difficult to sort both by classical mechanical, hydraulic, air-gravity, pneumatic methods and by less conventional electrostatic, corona or corona-electrostatic separation techniques for granular materials [5 - 10].

The aim of the present paper is to validate a method of electrostatic separation that might improve the traditional waste processing technologies. Each of these materials is characterized by a different composition and structure, which make them behave differently under the action of intense electric fields [7].

Table 1
PLASTIC MATERIALS TO BE RECYCLED FROM ELVs

ELV part	Main types of plastics	Approximate weight in an average car (kg)
Bumper	PS, ABS, PC/PBT	10.
Seating	PUR, PP, PVC, ABS, PA	13.
Dashboard	PP, ABS, PC, RUBBER, CARBOARD	7
Fuel system	HDPE, POM, PA, PP, PBT	6
Body (including panels)	PP, PPE, UP	6
Under-bonnet components	PA, PP, PBT	9
Interior trim	PP, ABS, PET, POM, PVC	20
Electrical components	PP, PE, PBT, PA, PVC	7
Exterior trim	ABS, PA, PBT, POM, ASA, PP	4
Lightning	PC, PBT, ABS, PMMA, UP	5
Upholstery	PVC, PUR, PP, PE	8
Liquid reservoirs	PP, PE, PA	1
Total		105

Experimental part

Table 1 lists the main plastic materials to be recycled from ELVs. Their type and amount varies from manufacturer to manufacturer.

The ability of particles to accumulate different charge depending on their conductivity enable their separation in the electric field of a bet-type electrostatic separator, as the one schematically represented in figure 1. In such a device, the powdery mixture is disposed in a mono granular layer on a conveyor-type electrode connected to the ground. This electrode transfers the granules to an area of intense electric field generated by a roll electrode powered by a DC high voltage supply. Due to the electrostatic induction phenomenon the particles that are better conductors (product A) get charged in contact with the conveyor and will be attracted to the roll electrode of opposite polarity. They stick to this electrode under the action of the electric image force and will move with it until a scraper detaches them so that to be disposed in the hopper A, while the uncharged less conductive particles are transported further on conveyer and collected at the end of it in a hopper B.

The design of experiments methodology adopted for the present study has the following advantages: possibility of studying simultaneously the effects and the interactions of a considerable number of factors, notable reduction in the number of experiments, high accuracy of the derived models. As the objective was the optimization of the

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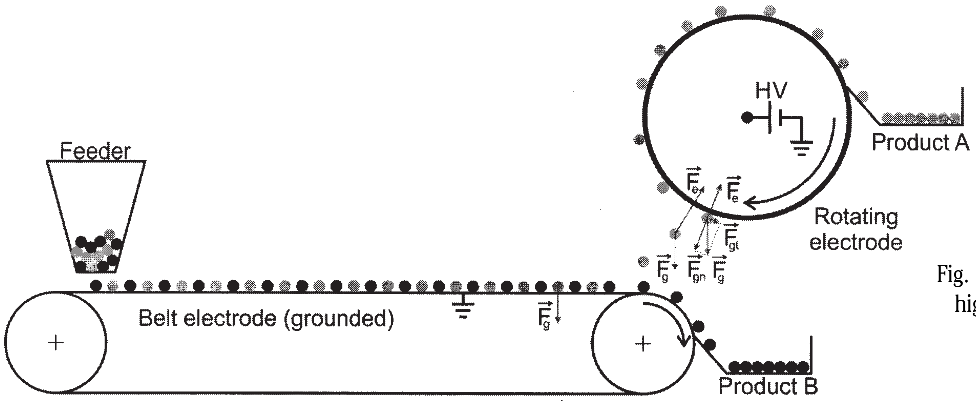

Fig. 1. Schematic drawing of the separator, highlightning the forces that act on the electrostatically charged powdery materials.

separation process, the response surface modelling method was employed to express the response y as follows:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_{11} x_1^2 + a_{22} x_2^2 + a_{12} x_1 x_2 \quad (1)$$

where a_i are the coefficients of a quadratic polynomial model and x_i is the normalized centered value for each factor u_i.

$$x_i = (u_i - u_{ic})/\Delta u_i = u_i^* \quad (2)$$

with

$$u_{ic}=(u_{imax}+u_{imin})/2; \ \Delta u_i = (u_{imax} - u_{imin})/2. \quad (3)$$

For the factors considered in the present study, i.e., conveyor belt velocity v and high-voltage U applied to the electrodes, the quadratic model of the response y, which can be the mass recovered at the electrodes or the purity of the products, will take the following form:

$$y = a_0+a_1 v^*+a_2 U^*+a_{12} v^*U^*+a_{11} v^{*2}+a_{22} U^{*2} \quad (4)$$

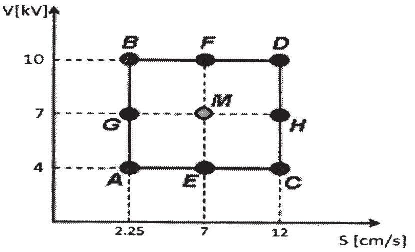

Fig. 2. Composite factorial experimental design for the study of the electrostatic separation of powdery mixtures

In order to obtain such a quadratic model the composite design (fig. 2) was employed for the present study [11, 12]. The experimental data were analyzed with MODDE 5.0 software (Umetrics,Sweden) [13], which calculates the coefficients a_i of the mathematical model, draws the response contours, and identifies the best adjustments of the parameters for optimizing the process. Moreover, the program calculates two statistical criteria: the "goodness of fit" R^2 and the "goodness of prediction" Q^2. The latter quantifies the ability of the model to predict the responses for new experimental conditions. A good mathematical model has criteria R^2 and Q^2 with the numerical value approaching unity.

Results and discussions

Electrostatic separation experiments

The set of experiments was carried out in ambient air (temperature: 18°C±1°C; relative humidity *RH* 50% ± 3%) on 5 g samples of a powdery mixture containing 52% of plastic materials acetate butadiene styrene - ABS, polycarbonate - PC and polypropylene - PP), the remaining 48% being represented by cardboard, rubber and textiles. The limits of the experimental domain were established based on some theoretical considerations, exposed in the next section of the paper, and by a series of preliminary experiments.

The more conducting materials (cardboard, rubber and textiles), designated as "product *A*", are subject to the Coulomb electric force:

$$F_Q = QE \quad (5)$$

Q being the electric charge carried by a particle and E the intensity of the electric field that act on it. With E proportional with U, by increasing the high-voltage applied to the electrodes, this force becomes strong enough to produce the lift-off of these particles from the belt electrode and to drive them to the rotating roll electrode. A particle of radius a will be pinned on due to the electric image force

$$F_i = Q^2 / [4\pi\varepsilon \, (2a)^2] \quad (6)$$

Part of the charge Q of the particles *A* may leak to the rotating roll electrode they are in contact with. This phenomenon is accompanied by a reduction of the electric image charge F_i. As a consequence some of the particles may detach from the roll electrode and return on the belt electrode, under the action of centrifugal and gravitational forces. In some cases, they may recover their charge in contact with the belt electrode and be again lifted-off by the Coulomb force F_Q. Rapid camera video-recoding put into evidence this "bouncing" motion between the two electrodes. This explains the relative poor purity of the less conductive product *B* (ABS, PC, PP), which is unpurified by *A* particles. From the above considerations it is expected that better results be obtained at higher applied voltages and hence stronger electric fields. However, the occurrence of parasitic corona discharges from the edges of the metallic belt electrode imposed U_{max} = 22 kV as the upper limit of the applied voltage. The lower limit U_{min} = 4 kV was suggested by several preliminary experiments showing that particles lift-off at this value of the applied high-voltage. The domain of variation of the belt velocity v was easier to establish. The lower limit v_{min} = 2 cm / s was imposed by the minimum quantity of one gram of material to be processed in one second for a belt length of one meter. The upper limit v_{min} = 12 cm / s was fixed by the characteristics of the belt electrode employed in the experiments. A composite factorial experimental design was conducted in the domain defined by the above considerations. The masses of products *A* (conductive)

Table 2
RESULTS OF THE COMPOSITE FACTORIAL EXPERIMENTAL DESIGN

Run	U [kV]	v [cm/s]	m_A [g]	m_B [g]	R_A [%]	R_B [%]	p_B [%]
1	4	2	0.35	4.13	7.81	92.19	66.67
2	22	2	1.84	2.13	46.35	53.65	93.06
3	4	12	0.25	4.33	5.46	94.54	57.89
4	22	12	1.79	2.33	43.45	56.55	87.50
5	4	7	0.41	4.26	8.78	91.22	55.77
6	22	7	1.84	2.25	44.99	55.01	90.16
7	13	2	2.05	2.46	45.45	54.55	94.12
8	13	12	1.71	2.58	39.86	60.14	86.21
9	13	7	1.76	2.57	40.65	59.35	90.14
10	13	7	1.77	2.68	39.78	60.22	91.04
11	13	7	1.76	2.58	40.55	5945	90.00

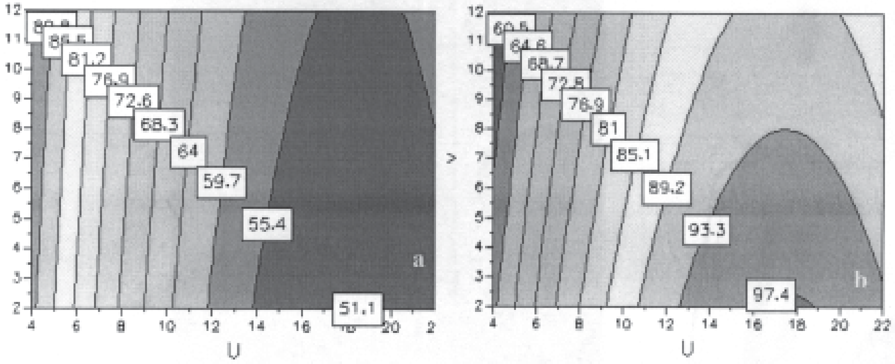

Fig. 3. a) MODDE 5.0 calculated equal-response contours of the relative mass R_B [%] of the recovered plastics as function of applied voltage U [kV] and belt velocity v [cm / s]; b) MODDE 5.0 calculated equal-response contours of the purity P_B [%] of the recovered plastics (B poduct), as function of applied voltage U [kV] and belt velocity v [cm / s]

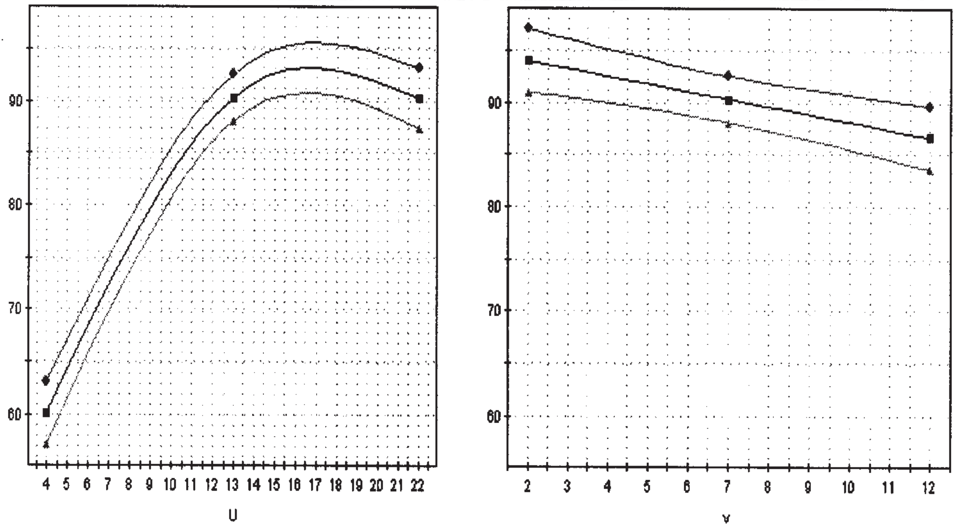

Fig. 4. Predicted purity P_B [%] of the recovered plastics (B product), as function of applied voltage U [kV] and belt velocity v [cm / s]. The upper and lower curves define the 95% confidence interval

and B (less conductive) are given in table 2. The same table also contains the values of

$$R_A\,[\%] = 100\,[m_A/(m_A + m_B)] \qquad (7)$$

$$R_B\,[\%] = 100\,[m_B/(m_A + m_B)] \qquad (8)$$

which designate the percentages of feed material recovered respectively as conductive A and non-conductive B products. It should be noted that R_B [%] = 1 - R_A [%]. As the purity of the conductive product P_A is almost 100% (practically none of the non-conductive granules can detach from the belt and be collected in the A hopper), reported in table 2 are only the values of P_B, i.e. the purity of the non-conductive product, expressed as the ratio between the mass of plastics granules and the total mass collected in the B hopper. The analysis of the purity was done by manual separation of the cardbord, rubber and textile from the plastics that represent the major product in that hopper.

Based on the data in table 2, the software MODDE 5.0 calculated the coefficients of the quadratic models for each of the output variables of the process R_A [%], R_B [%], P_B [%]. Thus, the relative mass of the recovered non-conductive B product could be expressed as:

$$R_B = 58.74 + 1.8\,v^* - 18.79\,U^* + 0.14\,v^*U^* - 0.51\,v^{*2} + 15.18\,U^{*2} \qquad (9)$$

This model has quite satisfactory statistical criterias $R^2 = 0.996$ and $Q^2 = 0.965$. The software MODDE 5.0 indicated that two of the coefficients in this model are not statistically significant, so they can be ignored. The new model:

$$R_B = 58.54 + 1.8\,v^* - 18.79\,U^* + 15.25\,U^{*2} \qquad (10)$$

is characterized by a slightly lower $R^2 = 0.995$ but a higher predictive power: $Q^2 = 0.988$. The equal-response contours obtained with this model are displayed on figure 3a. According to this model, for a low belt velocity v = 2 cm / s and a relatively high applied voltage $U \cong 18.5$ kV, 51.1% of the in-feed material will be recovered in the non-conductive B product. The purity of the non-conductive B product could be modelled by the following second order polynome:

$$P_B = 89.65 - 3.71\,v^* + 15.06\,U^* + 0.81\,v^*U^* + 1.64\,v^{*2} - 15.56\,U^{*2} \qquad (11)$$

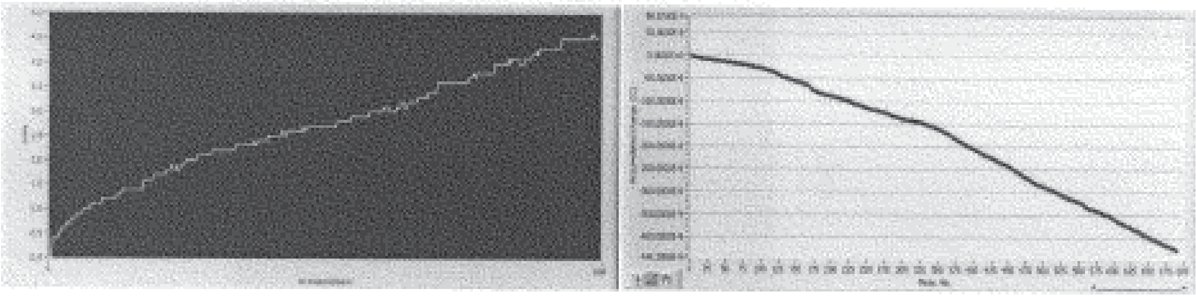

Fig. 5. Real-time data acquisition of the mass m [g] and the charge Q [nC] of the conductive material extracted as A product

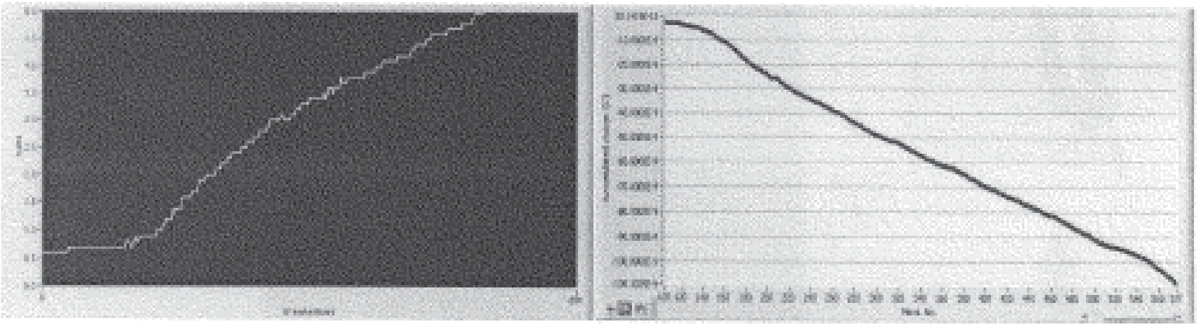

Fig. 6. Real-time data acquisition of the mass m [g] and the charge Q [nC] of the conductive material extracted as B product

with $R^2 = 0.989$ and $Q^2 = 0.904$. By eliminating the non-significant coefficients in the polynome, the model becomes ($R^2 = 0.985$ and $Q^2 = 0.956$):

$$P_B = 90.03 - 3.71\,v^* + 15.06\,U^* - 15.13\,U^{*2} \qquad (12)$$

The maximum purity $P_B \cong 97.54$ is obtained for a belt velocity $v = 2$ cm / s and an applied high-voltage $U \cong 17.5$ kV (fig. 3b). This can be easily explained by two interrelated facts : at low values of the velocity, the more conductive granules spend enough time in the electric field zone for getting well charged; at high values of the applied voltage, the electric field is more intense, so that the respective granules charge better (by conductive induction) and are practically all lifted-off the belt electrode. At applied voltages higher than 18 kV, the intensity of the electric field is such that the granules execute the “bouncing” motion described earlier, so that reducing the purity of the B product (fig. 4.a). At higher belt velocities v, the particles spend less time in the electric field zone. Part of the conductive particles remain on the belt electrode and contamiantes the plastics collected in the B hopper. Thus, the purity of the B product decreases with the increase of v, as shown in figure 4.b)

Electrical charge measurements

In this series of experiments, carried out at $U = 10$ kV and $v = 12$ cm / s, the products of the separation of 10 g of the powdery mixture originating from the processing of instrument panels ELV were collected in two Faraday pails connected to two electrometers (model 6415, Keitheley Instruments), that enabled the continuous measurement of the electric charge using a PC. The acquisition and processing of experimental data was performed using an ad-hoc virtual instrument, developed in the LabVIEW environment [14]. The mass of the products is measured in a continuous manner with electronic balances (resolution 0.1 g) positioned under the containers and connected to a computer via two RS232 connectors.

Both the mass m and the charge Q of the granules collected as the A product vary linearly with time, as displayed on the screen of the virtual instrument (fig. 5). The charge/mass ratio of this product is roughly Q/m ≅ 100 nC / g, a value that can be obtained by deviding the final values of the charge (Q = - 444.3 nC) and of the mass (m = 4.5 g) in the A hopper.

The mass m and the charge Q of the granules collected as the B product display also a linear increase with time, in absolute values (fig. 6). Suprisingly, the charge of the B product is also negative. However, the charge/mass ratio of this product is roughly $Q/m \cong$ - 20 nC / g, much lower than that of the A product. This negative charge is due to the conductive impurities that charge in contact with the belt electrode, but at levels that are too low for them to be lifted-up. Under the condition of this experiment, these impurities represent more than 20% of the B product.

Conclusions

The belt-type separator is an effective equipment for the recovery of plastics from powdery wastes generated at the outlet of standard mechanical recycling processes of the instrumentation panels of ELVs. More than 99% of the plastics contained in such wastes can be recovered in a product containing less than 5% of impurities (cardboard, textiles, rubber,..). Using a 1 m wide belt, these performances can be atteined at a throughput of 1 g/s (i.e., 3.6 kg/h), which is enough for treating the relatively small quantities of such wastes that should be treated in a recycling plant. This separation method can be applied to other powdery mixtures containing materials characterized by different electric conductivities, in the recycling industry, but also in mineral beneficiation or in food processing.

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References

1. VERMEULEN I., CANEGHEM VAN J., BLOCK C., BAEYENS J., VANDECASTEELE C., Automotive shredder residue ASR: Reviewing its production from end-of-life vehicles ELVs and its recycling, energy

or chemicals' valorisation. / Journal of Hazardous Materials, 190, 8–27, 2011

2. SAUERT F., SHAUB, M. CHRIST, F. RITTER J., RESHMENT – an ASR process for maximized recycling, reuse and recovery, Proceedings of the 2002 Environmental Sustainability Conference and Exhibition, SAE, 3757, 2010.

3. TOTH R., SAPLONTAI V., DOBREAN D., SAPLONTAI, M., PLESA C., MOLDOVAN M., MORAR R. Electrostatic Separation Combined With Classical Methods Of Recycling The Plastics From End-Of-Life Vehicles./ Buletinul AGIR nr. 3, 887-892, 2012

4. KUROSE K., OKUDA T., NISHIJIMA W., OKADA M., Heavy metal removal from automobile shredder residues ASR, J. Hazard. Mater., B137, 1618–1623, 2006

5. ANDERSEN F., LARSEN H., SKOVGAARD M., Projection of end-of-life vehicles: development of a projection model and estimates for ELVs for 2005–2030, ETC/RWM working paper 2008/2, Copenhagen, 2008.

6. JODY B.J., DANIELS E.J., End-of-life Vehicle Recycling: The State of the Art of Resource Recovery from Shredder Residue, Energy Systems Division, Argonne National Laboratory, 2006.

7. KOHNLECHNER R. AND DASCALESCU L., "New applications for standard electrostatic separators", Proc. of the IEEE Industry Applications Society 40th Annual Meeting, 2-6 Oct. 2005 Hong Kong. Conference Record. 4, 2569-2572, 2005.

8. CĂLIN, L., MIHĂLCIOIU, A., IUGA, A., DĂSCĂLESCU, L. Controlling particles trajectories in free fall separators, Proceedings of ESA/IEJ/IEEE-IAS/SFE Joint Conference on Electrostatics, Berkely, California, June 6-9, 2006, 863, 2006.

9. MORAR R., IUGA A., CUGLESAN I., MUNTEAN O., AND DASCALESCU L., "Iron ore beneficiation using roll-type high-intensity electric field separators", IEEE Transactions on Industry Applications, 35, 1, 218-224, 1999

10. BILICI M., DASCALESCU L., DRAGAN C., FATI O., IUGA A., AND SAMUILA A., "Tribocharging and electrostatic separation of mixed granular solids in fluidized bed devices", IEEE Trans. Diel. Electr. Insul., 18, 1476-1483, 2011

11. N. L. FRIGON AND D. MATHEWS, Practical Guide to Experimental Design. New York, NY, USA: Wiley, 1996.

12. ERIKSSON L., JOHANSSON E., KETTANEH-WOLD N., WIKSTRÖM C., AND WOLD S., Design of Experiments. Principles and Applications. Stockholm, Sweden: Learnways AB, 2000.

13. MODDE 5.0. User Guide and Tutorial, Umetrics AB, Umea, Sweden, 1999.

14. BILICI M., DASCALESCU L., BARNA V., GYORGY T., RAHOU F., SAMUILA, A., Experimental modeling of the tribo-aero-electrostatic separation of mixed granular plastics, IEEE IAS Annual Meeting, Orlando, FL, Paper EPC 227, 201

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