# LUNAR RESOURCE PROCESSING USING SOLAR ENERGY— A RESEARCH PROJECT STATUS REPORT

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## Abstract

Many candidate processes for utilizing lunar resources will require significant quantities of thermal energy. Concentrated solar energy is one potential source for such thermal inputs, particularly for surface operations that are of short duration and/or require a degree of mobility not available from centrally located nuclear systems. Because of the attractiveness of this energy option, McDonnell Douglas, the Space Studies Institute, and Alcoa Research Laboratories are conducting a joint research project to develop solar energy technology for lunar resource processing. In addition, McDonnell Douglas is also working with the Shimizu Corporation in the specific field of rock breaking. A key asset for this effort is a 75-kW$_{\text{thermal}}$ solar concentrator that McDonnell Douglas developed during a previous terrestrial energy program. This paper reports on the progress of this research in the areas of melting lunar simulant, postmelt processing, rock breaking and welding, and also identifies engineering issues that require attention in future research.

## Introduction

Because of the potentially major cost savings in lunar base operations that can be achieved through the use of local lunar resources, interest in the technology needed to find, extract, process and apply these resources (particularly oxygen) has grown significantly during the past several years[1,2]. One response has been the creation of a joint research project involving McDonnell Douglas Space Systems Company (MDSSC), the Space Studies Institute (SSI), and Alcoa Research Laboratories[3-6]. This project is studying the feasibility of utilizing solar energy for processing operations that require substantial thermal energy inputs, such as the production of crystallized cast basalt structures, glass composites, and hardened landing pad surfaces. These particular products have received priority in the team's initial research because they and their related production equipment can be kept simple enough for implementation during the earliest stages of a lunar base. Additionally, in a related effort, MDSSC is cooperating with Shimizu Corporation of Japan to conduct preliminary demonstrations on the use of intense solar flux for rock breaking, which may be necessary for preparing large surface areas, tunneling, and/or excavating subsurface ores. The long-term goal of all these tasks is to determine viable applications and to eventually develop prototype facilities for a lunar base.

The key element in conducting this early hardware-oriented research is the 75-kW$_{\text{thermal}}$ solar concentrator shown in Figure 1. This device, located at MDSSC's Solar Energy Test Facility in Huntington Beach, CA, can achieve concentration ratios exceeding 10,000 suns (or equivalently, energy densities of 1400 W/cm$^2$ on the lunar surface).* With such a concentrator, early hardware demonstration tests can uncover issues that may be overlooked by analytical studies while also providing investigators an intuitive understanding of the fundamental processes.

This solar concentrator was originally developed in the early 1980s for a terrestrial energy program and consequently is over-designed for an actual lunar system. Future

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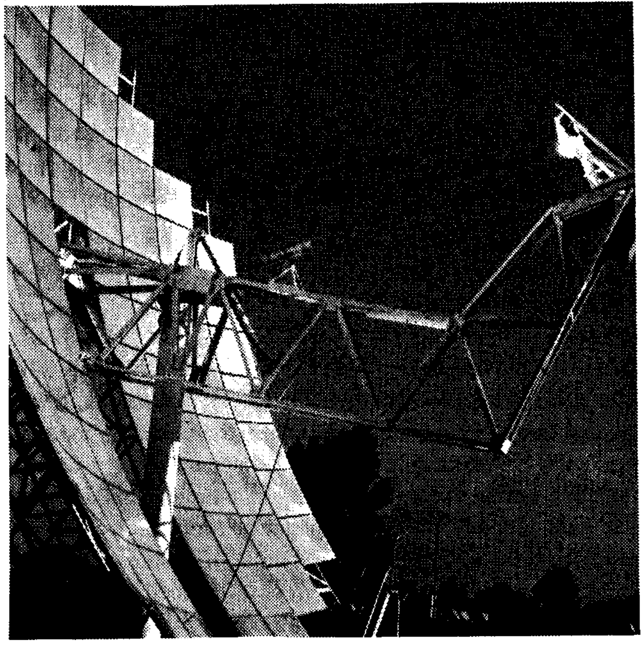

**Fig. 1 McDonnell Douglas solar concentrator with melt containment crucible.**

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**NASA has sponsored solar energy-based processing research using a Fresnel lens concentrator, but the total energy and sample masses involved were magnitudes smaller than those possible with the 75-kW MDSSC concentrator[7].*

studies will include the generation of a refined concentrator design that is optimized for both the lunar environment and specific resource processing applications. Table 1 presents a partial list of issues that will influence this new design.

The following sections report on the progress and observations generated by several of the recent research tasks that have been undertaken using this unique test facility.

**Table 1 Environmental factors and requirements influencing the design of solar processing facilities on the lunar surface**

| Issue | Concentrator | Crucibles, molds |
|---|---|---|
| Absence of wind loads | X | |
| Reduced gravity | X | X |
| Slower sun-tracking rates (0.6 deg/hr versus 15 deg/hr on Earth) | X | |
| Smaller seasonal changes in the sun's angle of declination (10 deg versus 47 deg on Earth) | X | |
| Constant solar flux (1400 W/m$^2$) | X | |
| Greater temperature variations (up to 300°C) over day/night cycle | X | X |
| Absence of convective heat losses | | X |
| Electrostatic, abrasive dust | X | X |
| Simple deployment/assembly | X | X |
| Remotely controlled and/or autonomous operation | X | X |
| Minimal maintenance | X | X |
| Mobility (optional) | X | |
| Variable focal length (optional) | X | |

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## Melting of Simulated Lunar Regolith

For several resource processing scenarios—oxygen extraction by magma electrolysis, surface paving, and the production of cast basalt and glass fibers—it will be necessary to melt the lunar regolith material. This phase change occurs at 1200 to 1300°C, which is easily achievable with the solar concentrator.* For the initial tests, it was decided to decouple melt studies from the postmelt processing, with emphasis placed on the mechanisms for energy transfer from the solar flux to the soil sample. This decision was based largely on the simpler environmental considerations associated with melting. Although, as shown in Table 1, the concentrator mirror design is influenced by a greater number of factors, these generally will affect its overall sizing. By comparison, those factors involving the lack of an atmosphere and reduced gravity may have relatively greater impact on the systems and techniques for postmelt processing.

The early work addressed the design and development of a simple melt-containment crucible that could be fitted to existing attachment structures on the solar concentrator (Figure 2). The prime requirement called for access of flux to the simulated lunar soil (hereafter referred to as simulant). For tests, most of the samples consisted of the Minnesota Lunar Simulant-1 (MLS-1) produced by the University of Minnesota[8]. Once the team had agreed upon a basic design, Alcoa then fabricated two identical crucibles out of an alumina ceramic that has a melt temperature of 1650°C.

**Fig. 2 First generation melt crucible.**

Upon delivery of the crucible to Huntington Beach, testing ran for a period of several months during mid-1990. (Reference 6 contains most of the raw data generated from these experiments.) Among the findings were that (1) conduction through these alumina ceramic crucibles was generally insufficient to melt the simulant—direct insolation was required, (2) additional insulation was needed to reduce both radiative and convective heat losses on the nonradiated portions of the crucible, and (3) because the simulant is such a good thermal insulator, even direct insolation on it tended to melt only the top several centimeters (Figure 3). To more fully melt an entire sample (which generally had a mass of about a kilogram), additional heat transport mechanisms were required to conduct heat below the surface. One approach that was implemented involved a platinum/rhodium liner. This conductor succeeded in fully melting the entire sample; however, upon solidifying, it bonded very tightly with the liner (Figure 4). This problem probably can be avoided for a continuous flow system. However, the facility must accommodate shutdown at the end of the lunar day without any blockage problems, while also avoiding direct exposure of the lining to vacuum if such a liner contains platinum. (This metal has a low vapor pressure. Alternative materials such as tungsten might

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**Even small concentrators can melt regolith. The desired size of an actual lunar-base concentrator will be determined by the required processing rates, quantifiable as mass flow, which in turn will be a function of overall base operations. Data generated here will help refine coefficients (e.g., energy transfer efficiency) that will enable improved parametric modeling of these functional relationships.*

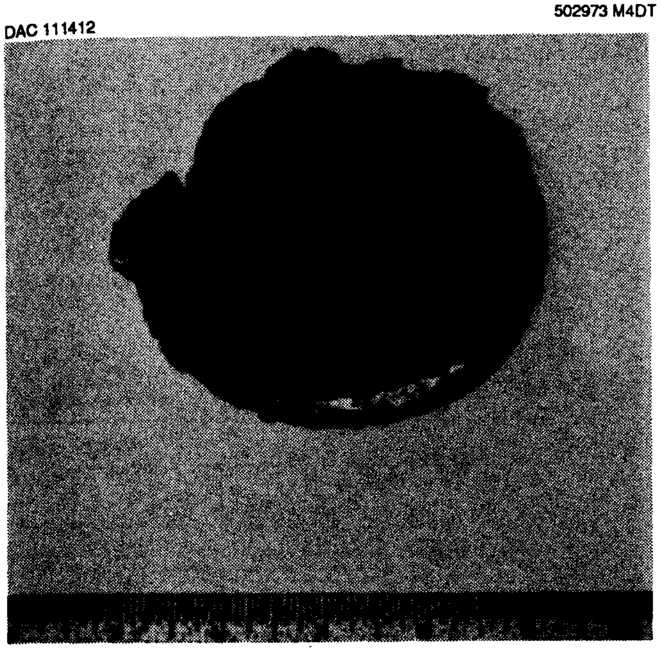

Fig. 3 Direct insolation melted only the top of the simulant sample.

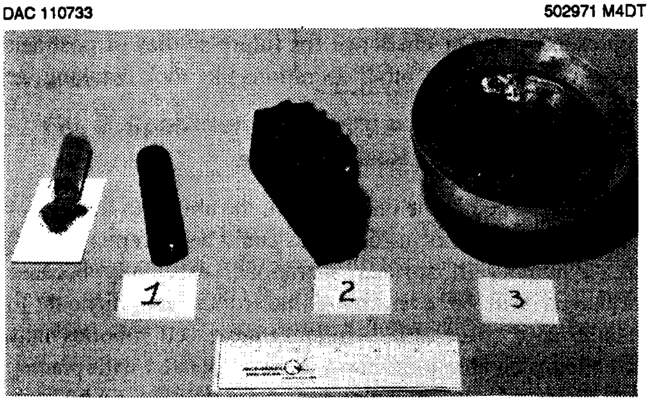

Fig. 4 Preliminary cast basalt products (1,2) and fully melted simulant sample in platinum/rhodium lining (3).

prove to be more effective in this nonoxidizing environment.) Additional research is underway to assess the effectiveness of spun crucibles and/or thermally conducting rods that are partially embedded in the sample.

Another significant observation was that even short-term exposures to the fringe of the focus area quickly degraded the crucibles over a limited number of test cycles. This degradation resulted from a combination of both thermal shock and direct melting of the leading edges. Future crucible designs will incorporate a wider orifice to avoid this problem.

A major limitation with these crucibles was that they lacked the capability to pour the melt into molds. Consequently, they also served as the postmelt containers. To provide greater postmelt thermal control and to also begin production of cast basalt pieces, a series of graphite molds were fabricated and substituted for the crucibles at the focus (Figure 5). In contrast to the alumina ceramic crucibles, the graphite molds were thin enough and adequate enough thermal conductors that the simulant could be melted without direct exposure to the flux. Totally enclosing the mold in a fibrefrax insulator after exposure then reduced outward heat flow, enabling a much longer cooling period at sustained high temperatures.

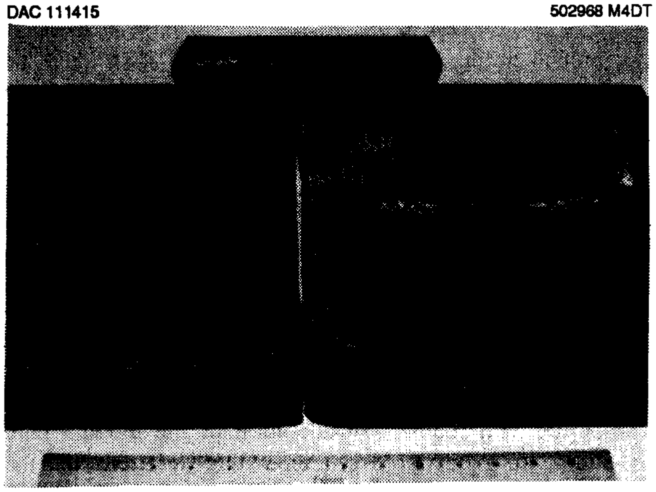

Fig. 5 Graphite mold for cast basalt production.

Figures 4 and 5 contain some of the early cast basalt items produced in this manner. The rods demonstrated compressive strengths of approximately 10,000 psi (two to three times that of terrestrial concrete) when tested using ASTM procedures[9]. In all cases, it was found that the cast basalt rods only took up 60 to 70% of the volume of the original simulant sample and that there was significant bubbling during the melt phase. Future tests in vacuum will help determine if the latter effect was a function of escaping atmospheric gases and/or the chemical release of volatiles that were originally bonded to the simulant.

As with the crucibles, the use of the graphite molds to first heat and then contain the melt severely limited the latter's lifetime (in these cases, sublimation of the exposed mold surface was the primary aging mechanism). For 1991, the MDSSC/SSI/Alcoa team is now developing a new crucible that incorporates several features to overcome these shortcomings. Specifically, it will incorporate a larger orifice for the incoming flux beam, as well as a pour spigot and an electrically controlled thermal valve. The first modification should reduce thermal stresses and thus material fatigue, while the latter ones will enable the pouring of the melt into other containers for postmelt processing. Furthermore, as mentioned previously, attention is being given to improving heat transfer to the entire sample, not just the surface, to ensure more complete melting.

## Postmelt Processing

In addition to the limited product data obtained from these tests, there exists a substantial experience base with terrestrial cast basalt (also referred to as abresist) manufactured commercially in places such as eastern Europe[10-12]. For example, one general procedure involves a 24-hr cycle in which the newly solidified basalt is first cooled to 800°C and kept there for several hours, during which time nucleation occurs. The cast is then brought down to ambient temperatures slowly to avoid cracking.

Implementing similar temperature profiles should be relatively easy on the moon. Reduced energy levels can be applied to the postmelt material, either directly by concentrators, through conductive containers, electric heaters, or possibly even high-power-density, fiber-optic cables.* The advantage of the last two options is that they can accommodate autoclave-type operation if desired, while also enabling quick modulation of the input energy. Cooling may necessitate the addition of radiator elements to the facility.

As mentioned previously, successful application of these control techniques for the attainment of optimal product properties will require consideration of the moon's hard vacuum, 1/6-g gravity, large temperature variations, and the totally anhydrous nature of the regolith. The first factor can be approximated reasonably well in ground-based test facilities and the MDSSC/SSI/Alcoa research team is starting to plan for such work, while the reduced gravity can be duplicated for short periods of time on a KC-135, which should be sufficient to assess melt flow rates. The study of longer-term phenomena, such as nucleation during cooling, will probably require the use of space-based centrifuges.

The lack of water in the lunar soil presents a challenge in efforts to define the properties of the end products. Of particular interest is the differences between simulant, which has relatively high water and $Fe_2O_3$ content, and the dry lunar regolith, in which the iron is only in the FeO state. An expected impact is that lunar glass structures and fibers should be stronger and less brittle[15]. There are also some indications that regolith melt viscosity could differ significantly from that of simulant, which would impact flow rates[16]. One implication is that although glass fibers were produced during the 1990 tests (Figure 6), the combination of different viscosity and lower gravity might render gravity-feed techniques impractical for fiber production on the moon. Pressurized force-feed system might overcome this problem, but at the cost of increased equipment. Thus, distinguishing the role of water in terrestrial experiments represents a major challenge for future studies of postmelt processes, as well as other operations like rock breaking, as discussed below.

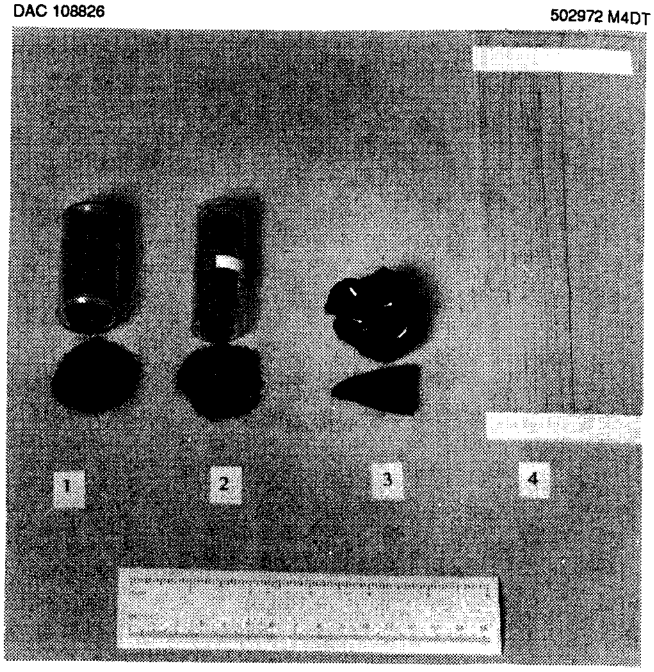

**Fig. 6 Glass fibers (4) were among the early products derived from MLS-1 (1) in initial solar concentrator tests.**

## Rock Breaking

As explained in the introduction, the ability to fracture or break up large rocks or rock-beds could be extremely useful for a number of surface operations, especially because ordnance will be even more hazardous and difficult to handle in a space suit. Although advanced robotics may eventually be able to perform tasks associated with placing and discharging such explosives, there will always be costs associated with transporting and storing these devices. A mobile concentrator, possibly used in conjunction with light pipes, represents a nonexplosive alternative that can also be used for some of the other applications described here, as well as the part-time production of electricity[17]. To explore this option, MDSSC is working with Shimizu, a large architectural and engineering firm based in Tokyo. Their background in rock mechanics for buildings and transportation infrastructures (roads, train tracks, subways and airports) and interest in lunar base operations[18] complements MDSSC's strengths in solar energy and space operations.

For these tests, MDSSC enlisted University of Minnesota's support to procure two basalt block specimens from the same quarry that the school obtains their source stock for MLS-1 simulant. Figure 7 shows the approximate shape and location of thermocouples, while Figure 8 shows the first specimen mounted in front of an array of quartz lamps that

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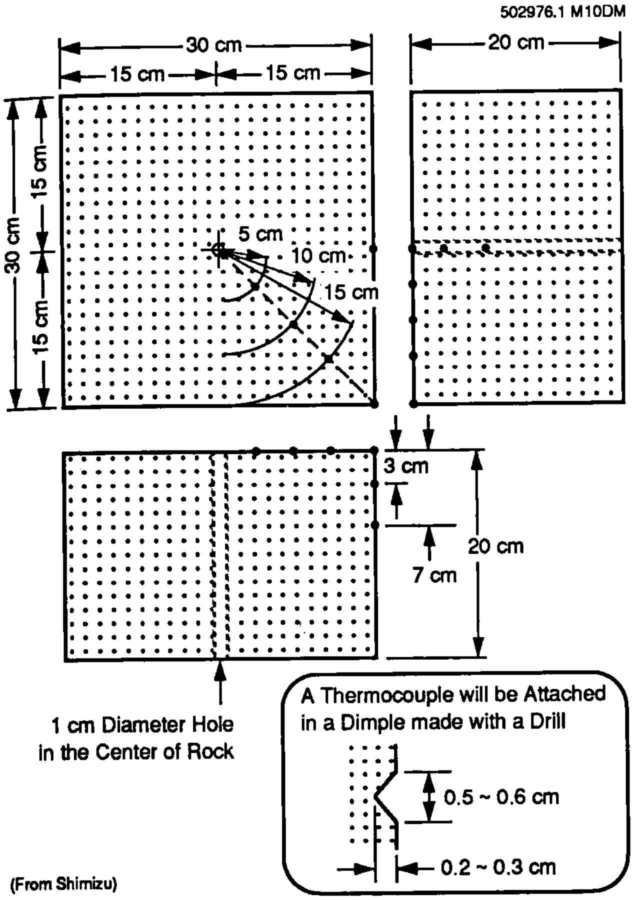
**Low-power, fiber-optic systems for transmitting collected solar energy already exist[13,14]. Additionally, there are optical fibers that can accommodate higher power densities—the design challenge appears to be coupling such cables to the flux collectors to achieve the required energy levels.*



(From Shimizu)

**Fig. 7 Specimen geometry and thermocouple layout.**

generated a steady flux of 5 W/cm$^2$. The second specimen was tested on the solar concentrator, at much higher flux levels (15–25 W/cm$^2$).* In both cases, the specimens were encased in fibrefrax insulation to inhibit heat flow except at the exposed surface. Such a condition is expected for materials on the moon.

The objective of these tests was to verify computer thermal models and to get matched characteristics with the MLS-1. These goals were accomplished successfully and additionally, several unexpected phenomena were observed. The first specimen fractured in a roughly parallel plane 10 cm from the exposed surface after 1.5 hr of irradiation from the quartz lamp array. On the second specimen, small fragments began popping off the exposed surface as soon as the flux was targeted on the specimen. Outgassing was also observed. It then fractured into major fragments and underwent extensive melting after less than 40 minutes at the increased flux levels.

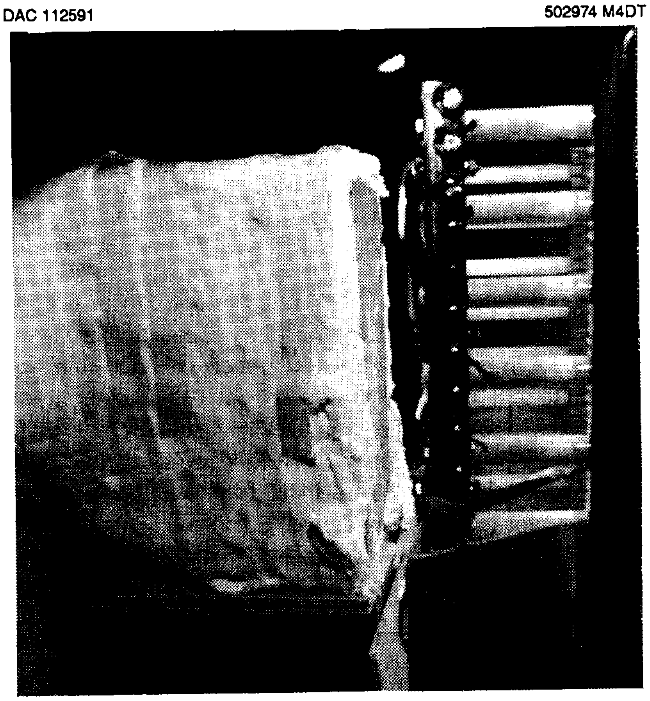


**Fig. 8 Test arrangement for quartz lamp tests.**

Analysis is underway to determine what role water played in these phenomena and hence, their relevance to lunar conditions. It may prove necessary to "dry-out" additional specimens and then conduct the tests either a very short time later on the concentrator or in a vacuum chamber. The latter option would provide a way to also measure what materials might be outgassed during such exposure. The flux intensity and modulation patterns may also prove to be important variables in controlling the nature of the fracturing.

If viable, these processes could see applications in removing and excavating large rock obstacles, or alternatively, they could serve as the first stage in breaking down large ore concentrations. Such operations could be enhanced by covering target areas with multilayer insulation just prior to lunar dawn when they are at their lowest temperature, and then later subjecting them to high-density solar flux at a more convenient time. This would maximize the thermal shock effect and would be aided by the fact that little heat will come in from surrounding material because of the lunar regolith's poor thermal conductive properties.

## Brick Welding

The final area of experimentation involves the solar welding of structural elements. A typical application would be the closure of domed structures that might be used for storage, life support, and/or thermal energy storage during the night. Although such vessels might not be man-rated, they could provide an important extension of pressurized volume in the early lunar base. Such operations will

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**The 75-kW concentrator was not designed to provide tight, real-time control of the flux density and associated flux pattern. With the daily and seasonal variations in solar flux and intermittent atmospheric effects, it currently is impossible to accurately adjust the concentrated flux levels irradiating a specimen. Therefore, the quartz lamp test served as a way to check rock properties, sensor operation, and data collection software coefficients before full-scale tests on the concentrator.*