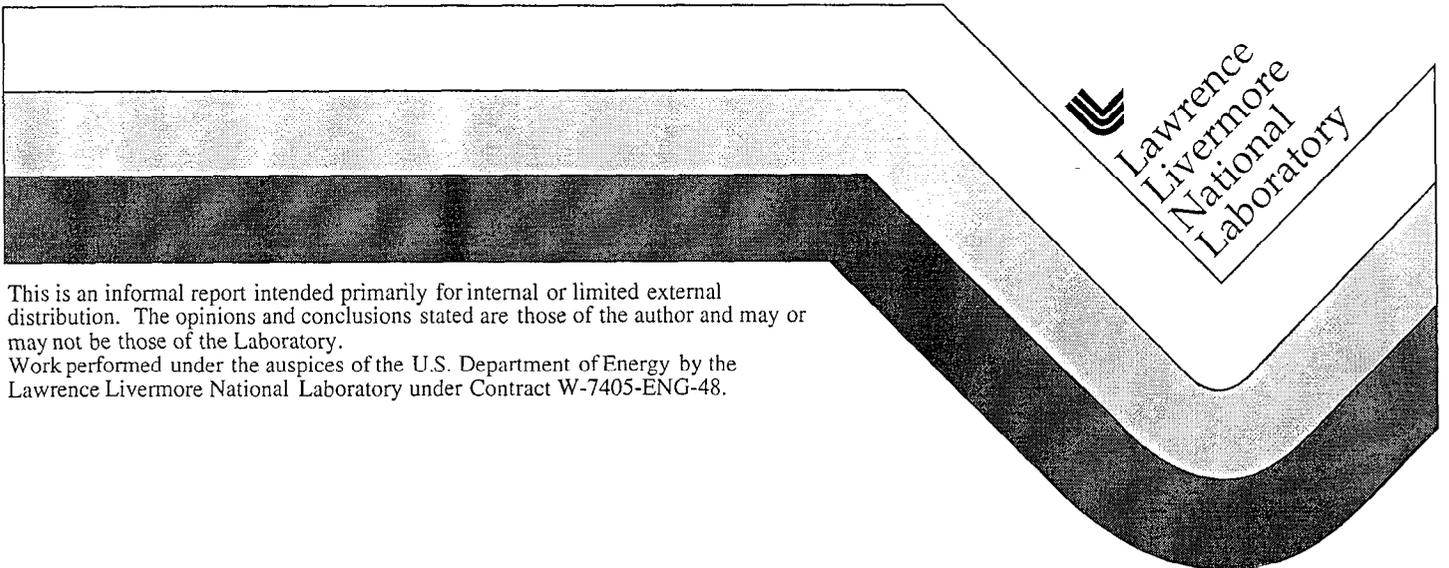


Expedited Technology Demonstration Project Final Report: Final Forms

Robert W. Hopper

May 1999



This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.
Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Expedited Technology Demonstration Project Final Report: Final Forms

Robert W. Hopper

**Lawrence Livermore National Laboratory
Expedited Technology Demonstration Project
Earth & Environmental Science Directorate
Livermore, CA 94550**

**Prepared for: U. S. Department of Energy
Oakland Operations Office
Waste Management Division**

May 1999

0. Summary

ETDP Final Forms was an attempt to demonstrate the fabrication and performance of a ceramic waste form immobilizing the hazardous and radioactive elements of the MSO/SR mineral residues. The ceramic material had been developed previously. The fabrication system was constructed and functioned as designed except for the granulator. Fabrication of our particular ceramic, however, proved unsatisfactory. The ceramic material design was therefore changed toward the end of the project, replacing nepheline with zircon as the sink for silica. Preliminary results were encouraging, but more development is needed. Fabrication of the new ceramic requires major changes in the processing: Calcination and granulation would be replaced by spray drying; and sintering would be at higher temperature. The main goal of the project—demonstrating the fabrication and performance of the waste form—was not achieved. This report summarizes Final Forms' activities. The problem of immobilizing the MSO/SR mineral residues is discussed.

1. Introduction

The Expedited Technology Demonstration Project (ETDP) is to demonstrate an integrated system for treating organic-based mixed wastes. It comprises three systems: Molten Salt Oxidation (MSO), Salt Recycle (SR), and Final Forms. MSO destroys the organic components of the waste. Salt Recycle periodically processes the MSO salt, separating halide salts and removing mineral residues from the sodium carbonate, which is then re-used. Final Forms immobilizes the mineral residues as a durable ceramic final waste form.

The ETDP system was originally designed to treat a variety of wastes from LLNL's mixed waste inventory, which is typical much of DOE's mixed waste. The mineral residues arise from the MSO input waste stream(s), and compounds introduced by the MSO process itself and by the SR process.

The ceramic final waste form must immobilize the hazardous and radioactive elements present; both the ceramic material and the process to make it must be adaptable to the variable composition of the filter cake; and a high waste loading is desirable. The ceramic is intended to satisfy federal and California leach resistance standards. The project is now in its close-out phase. Attempts to commercialize the treatment system are in progress.

The Final Forms system was installed late in the ETDP project and became fully operational only in December 1998. Process difficulties were soon encountered. Most had been anticipated but were expected to be relatively minor and solvable with straightforward process development and optimization; in the event, they proved serious and intractable. By the end of February 1999 it was recognized that the problems were fundamental and that a major reassessment of the Final Forms system was needed. These are described in our monthly reports^[2].

This report summarizes the Final Forms experience and status, with emphasis on recent developments. An extensive collection of ETDP (including Final Forms) documentation will be permanently archived on a compact disk (Ref. 1). Included are two addenda to this report (Refs. 3-4). The design and operation of ETDP is described in Refs. 5-6; for Final Forms, see also Ref. 7.

2. Design of the Ceramic Material, Process and Facility.

As originally conceived, ETDP was to be capable of treating a wide variety of organic-based wastes—liquid and solid, halogenated and non-halogenated, and low- and high-ash. Mineral residues derived from LLNL solid mixed wastes (primarily lab trash) are expected to be dominated by Si, Al, Mg, K, Zn, Ca and Fe. The filter cake of the MSO/SR will also contain the filter aid used in SR, and significant amounts of the oxides of Cr, Fe and Ni resulting from corrosion of the MSO reaction vessel. (The filter cakes from the ETDP demonstrations were *primarily* filter aid, and the Cr, Fe and Ni oxides were the principal minor components. This was a consequence of the small amount of waste treated in each demonstration and is atypical of extended waste treatment operations.) Any of a wide variety of other elements may be present in minor or trace amounts. In an actual waste processing setting, waste loadings could be optimized by blending residue batches, but this is impractical for ETDP.

The final waste form was to be a ceramic. Taking into account the above requirements—the relative importance of each was not well appreciated at the time—the ceramic was an adaptation of Synroc D^[8]. The ETDP ceramic waste form was the subject of extensive development work.^[9] The ceramic comprises four principle crystalline phases chosen because (1) they can be fabricated as a durable ceramic using standard and economical ceramic processing methods; and (2) they can incorporate, either as major constituents or by ion substitution, all of the dominant elements just mentioned, and most of the hazardous and radioactive elements of concern.

These phases, with their base compositions and immobilization roles are as follows:

nepheline	$\text{Na}_2\text{O}\cdot\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$	[Si, K]
spinel	$\text{MgO}\cdot\text{Al}_2\text{O}_3$	[Mg, transition metals V-Ga except Cu^{1+}]
zirconolite	$\text{CaO}\cdot\text{ZrO}_2\cdot 2\text{TiO}_2$	[Sr, Hf, tetravalent lanthanides and actinides including U^{4+}]
perovskite	$\text{CaO}\cdot\text{TiO}_2$	[Sr, Pb, trivalent lanthanides and actinides]

The ceramic is formulated with an excess of titania (TiO_2) to stabilize the perovskite and zirconolite. A ceramic waste form “design” is simply the specification of the relative amounts of each phase. This just a matter of matching the phases to the filter cake composition, subject to the constraints that ~5 mole % should be rutile and each of the other four should be >10 mole %. Typical developmental formulations, bench-scale process descriptions, characterizations and performance data may be found in Refs. 5, 6 & 9. The microstructure of a typical developmental ceramic is given in Ref. 3.

ETDP was at the pilot-plant scale. The main process steps and equipment items (*italics*) are as follows:

- Ceramic design and recipe.
- Batching: formulating a batch comprising a mixture of residues, ceramic precursors, and other reagents; done in an ordinary *fume hood*.
- Wet Milling: mixing and comminuting the batch in an *attritor*;
- Calcining: drying and calcining it in a *rotary calciner*;
- Granulation: granulating the resulting powder in a *granulator*;
- Pellet Pressing: forming pellets by cold-pressing the granulated powder in a *pellet press*.
- Sintering: sintering the pellets in a *large tube furnace*.
- Miscellaneous activities: material transfers between the various pieces of equipment, process control tests (including test sintering in a *small tube furnace*), quality control tests, and equipment maintenance and refurbishment.

These steps and the associated equipment were described in more detail in Refs. 5 & 7. To minimize handling of dusty powders, the system was designed with closed connections between equipment items whenever practical. A process functional flow diagram and a floor plan showing the layout and material flow are given below (Figs. 1-2). Photographs showing the ETDP Final Forms system are given in Ref. 4.

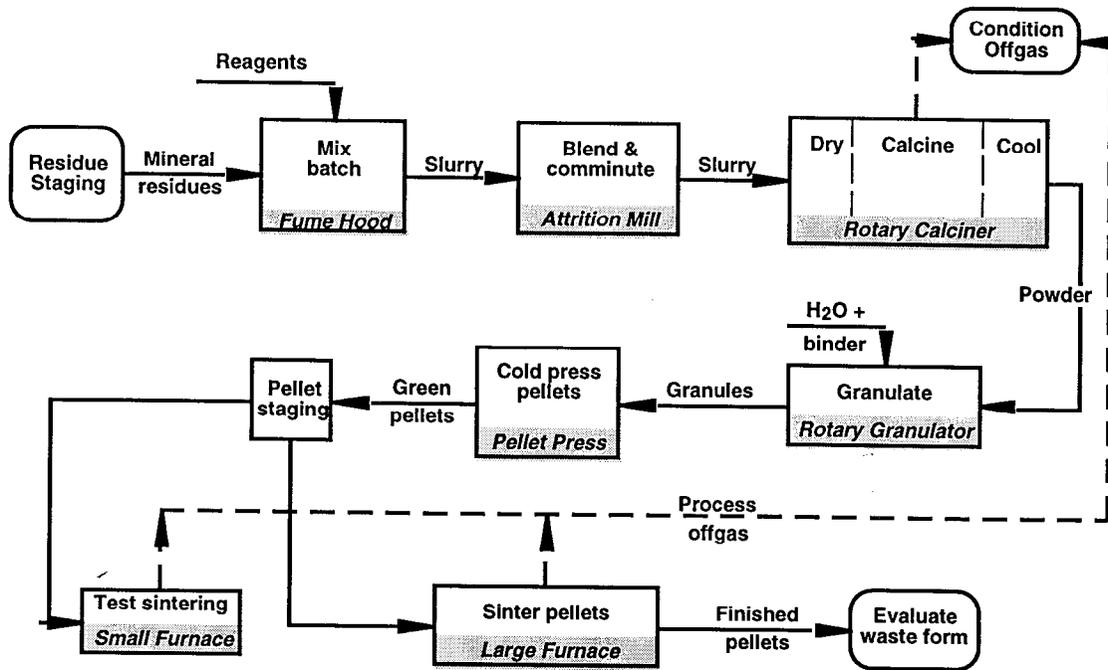


Figure 1. Ceramic waste form process functional flow diagram. Process wastewaters generated are not shown.

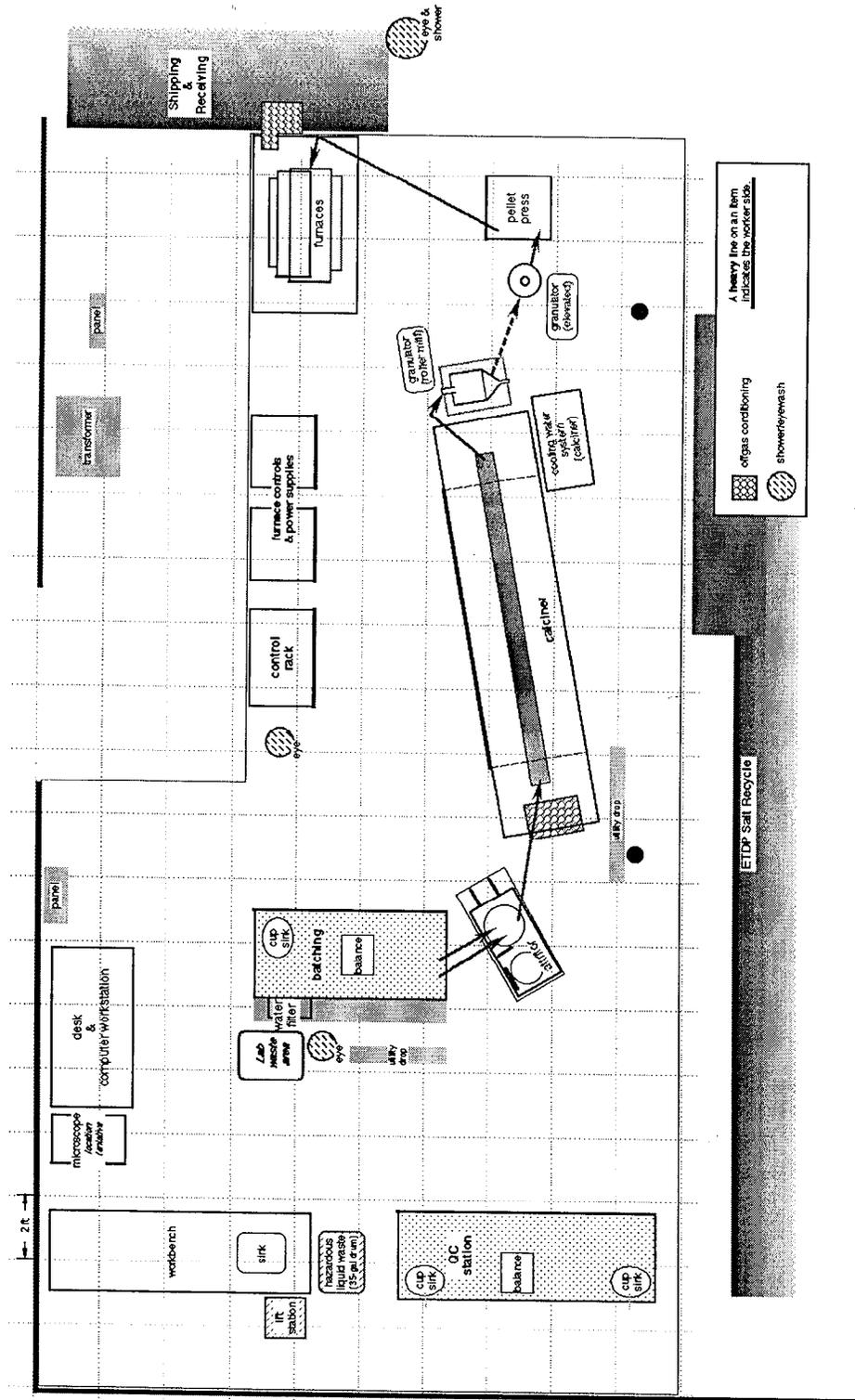


Figure 2. Floor plan of Final Forms equipment layout. Arrows indicate material flow.

3. Processing Experience and Recent Developments

Final Forms' status and plans at the end of FY1998 were summarized in Ref. 6. As mentioned in Section 1 of the present report and described in Ref. 2 (see also Ref. 10), experience with the system during FY1999 proved disappointing. The salient points of our experience are summarized and discussed in this section.

Our main difficulties centered (as had been anticipated) on the calcination and granulation steps: excessive caking occurred in the calciner, and the calcine adhered to the interior of the granulator. Incremental improvements were achieved, but the results were never fully satisfactory. Ultimately, the granulation step was replaced by first ball milling the calcine to break up the calcine and blend the organic binder and lubricant; and then forming a free-flowing powder by "blending" the milled material in a blender. With a better choice of milling and blending equipment, this may be a feasible process.

Powders having excellent uniformity and flow properties are absolutely necessary for pressing pellets with our sliding anvil press. This is because the press is controlled by setting the ram *displacement* rather than the ram *force*. The pressing pressure therefore depends on filling the cavity with very consistent amounts of powder.

Most of our worst processing problems were associated with components needed to form the nepheline phase. Nepheline was our "sink" for silica. Salt Recycle used diatomaceous earth (DE, an amorphous silica) as their primary filter aid, and the filter aid is the principal component of the SR mineral residues. In order to reduce amount of nepheline needed in the ceramic, experiments using other filter aids were carried out by SR at Final Forms' request. Precoating the filters with a relatively thin layer of DE followed by layers of kaolin and titania (these also being components of the ceramic formulations) seemed satisfactory, but further testing would be useful.

In retrospect, however, the ceramic *material* was probably poorly chosen. Historically, nepheline was included in Synroc D to immobilize sodium, high concentrations of which are present in much of U. S. high-level reactor waste. (Reactor rod cladding was dissolved in nitric acid, which was then neutralized with NaOH.) Nepheline had always been a troublesome phase, but alternatives appeared even less satisfactory.^[11] In addition to being our sink for silica, the potassium analogue of nepheline was to be our sink for the potassium in the residues from processing high-ash wastes—kaolin being a prominent component of them. However, ETDP processing was almost exclusively of low-ash wastes. In the absence of significant levels of sodium or potassium, alternative phases for the silica become attractive.

Obviously, this is a fundamental change of the Final Forms design philosophy, one which certainly calls for an extensive review. Its advisability depends on the wastes to be processed. It was nevertheless decided, in February, somewhat desparately, to redesign the ceramic material.

The first attempt was to replace nepheline with mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$). This failed because zircon ($\text{ZrO}_2 \cdot \text{SiO}_2$) formed instead. Naturally, the quantities of the phases in the ceramic was not as desired. A new formulation was designed with zircon as the replacement for nepheline. The target design phase assemblage (mole %) and roles follows:

zircon	40%	$\text{ZrO}_2 \cdot \text{SiO}_2$	[Si]
spinel	25%	$\text{MgO} \cdot \text{Al}_2\text{O}_3$	[Mg, V-Ga except Cu^{1+}]
zirconolite	18%	$\text{CaO} \cdot \text{ZrO}_2 \cdot 2\text{TiO}_2$	[Sr, Hf, tetravalent lanthanides and actinides including U^{4+}]
perovskite	12%	$\text{CaO} \cdot \text{TiO}_2$	[Sr, Pb, trivalent lanthanides and actinides]
rutile	4%	TiO_2	[phase stabilization]
baddeleyite	1%	ZrO_2	[phase stabilization]

Processing through pellet pressing was satisfactory. Upon sintering, the phase assemblage approximates that desired. Phases identified by X-ray diffraction included each of the above plus magnesium titanate ($\text{MgO} \cdot 2\text{TiO}_2$), cristobalite (SiO_2), and a second calcium zirconium titanate given nominally as $\text{CaO} \cdot 1.2\text{ZrO}_2 \cdot 1.8\text{TiO}_2$. (Identifications are somewhat uncertain; the diffraction patterns are very complex. No quantitative analysis was attempted.)

Finally, this formulation was modified by adding 1 wt% each of Cr_2O_3 , Fe_2O_3 , NiO and CeO_2 . (The first three are the principal minor components of MSO/SR, being products of corrosion of the inconel MSO reactor vessel; and the last is a surrogate for UO_2 .) The phase assemblage was essentially the same. Minor changes included shifts in peak positions, which might be attributed to dissolution of the additions—as desired. No further analyses were undertaken, however, in part for want of time and money but also because the sintered pellets were not well-densified.

This had been expected: zircon requires much high sintering temperatures than nepheline. Sintering had been for 4 hours at 1210°C , which is about the limit for comfortable operation with our Inco 600 retorts. The pellets had reasonable handling strength but nowhere near that achievable—and needed for waste form durability. Retained open porosity was (37 ± 1) vol%, which is unsatisfactory. Linear shrinkage was (8.5 ± 0.5) %. Because of the high porosity, implying a very large surface area, no leach testing was done.

These results are encouraging but that is all. Extensive development of the material, similar to that done for our original ceramic design would be required prior to acceptance. Important processing advantages would accrue. Calcination would be unnecessary, as the reagents used in the zircon-based ceramic do not require it; and granulation would be eliminated. Instead, the components would be milled in an attritor, and the resulting slurry would be spray dried. The process would be simpler and would undoubtedly yield a much better powder. Sintering

would entail higher temperatures and therefore different furnaces; but these would still be standard.

Several planned activities were cancelled, mostly in response to processing difficulties. These include the following:

- Because of Final Forms' processing difficulties, no authentic residues from the MSO/SR process were treated by Final Forms.
- Because MSO processed little high-ash waste (surrogate or authentic), Final Forms could not evaluate suitability of the Final Forms ceramic and process for MSO/SR residues of this type.
- The inorganic compounds expected from the MSO treatment of typical mixed wastes, both high- and low-ash, may be affected by their residence in the MSO molten salt bath. A planned experiment to introduce such compounds by suspending them in oil and injecting them into the MSO reactor was not carried out.

With three exceptions, all hazards control procedures and design features^[7] proved satisfactory:

- The flapper valve for steam release on the calciner proved unsatisfactory in practice. It was replaced by a solenoid valve controlled simultaneously with the process air inlet solenoid valve.
- Contact switches had been installed on the entries of the tube furnace retorts. Their purpose was to shut off the process air input to the retort were it opened inappropriately (by operator error). The mounting arrangement of the switch failed to take into account the thermal expansion of the retorts. This would have been corrected (easily) had operations reached the point of sintering radioactive or hazardous material.
- Refurbishing the sliding anvil and tool set of the pellet press entails lapping the items with a diamond paste suspended in naphtha, which is flammable. As a precaution, the OSP required that the lapping be done in a fume hood. This was needlessly conservative, proved burdensome to the operator, and made it virtually impossible to perform the lapping to normal standards of perfection. Less stringent conditions on the lapping would have sufficed.

4. Status of the Ceramic Waste Form System

The ETDP facility is being dismantled and will be placed in storage pending transfer to an industrial partner. (Contacts for dismantlement are P. C. Hsu and T. D. Ford.) The Final Forms system, with the exception of the calciner, has been shut down in preparation for this. The calciner is being loaned to the National Ignition Facility with the understanding that it will be returned in essentially the same configuration and condition if needed by an industrial partner. (The NIF contacts are J. H. Campbell and C. B. Thorsness.) All other equipment items have been cleaned and are ready for storage. There were no contamination

problems, as no radioactive or significantly hazardous materials had been used. Formal shutdown procedures were followed.

Primary documentation of Final Forms may be found in Ref. 1. Supporting documentation is being retained by R. A. Van Konynenburg (ceramic R&D data) and R. W. Hopper (miscellaneous notes, drawings, designs, analyses, data, process development lab notebooks, specimens, etc. not appropriate for formal archiving).

5. Discussion and Recommendations

The ETDP integrated MSO-based treatment system evolved over a period of years. The MSO/SR combination has been convincingly demonstrated with halogenated and non-halogenated organic liquids, and with carbon suspended as fine particles in an organic carrier liquid. Whatever the potential for treating coarse high-ash solid wastes, it seems fair to say that MSO/SR is a “natural” for these wastes. (Some demonstration was done with coarser low-ash solids, but more work is advisable.) With this experience in hand, a reappraisal of the sort final waste form best suited for MSO/SR is timely. The regulatory context remains complex and subject to change, and varies from state to state. The existence of a licensed low-level mixed waste disposal site (Envirocare, Utah) is an important consideration.

Consider the MSO/SR treatment of low-ash waste in rational industrial operation. (By “rational” I mean technologically and fiscally, in both the design of the system and its operation.) The volume of mineral residues produced will be very small compared with the volume of waste treated. The need for a dedicated system to immobilize (against leaching) the hazardous constituents of the mineral residues is surely questionable. Consider the following:

- The capital investment and operating costs of a treatment are substantial.
- The benefit of destroying a large volume of organics (often toxic) is large.
- Most of the remaining hazardous and/or radioactive components will typically be concentrated in the mineral residues, whose volume is small.
- For halogenated hydrocarbons, the total volume reduction may not be large, but converting them to NaCl is undoubtedly beneficial.
- Exceptions involving radioisotopes not readily separated from NaCO₃ and/or NaCl do not negate the above.

Under these circumstances, the incremental benefit of ceramic waste form capability is small relative to the cost increase, and a potentially attractive disposal option is simply to ship the mineral residues to a suitable disposal site.

Immobilization may, however, be deemed preferable or necessary (e.g., by regulation). In that case, a glass rather than a ceramic waste form should be evaluated. ETDP's (and MWMF's) final waste form was chosen because of the need to immobilize the residues of typical high-ash LLNL solid mixed waste containing, as noted previously, significant concentrations of Si, Al, Mg, K, Zn, Ca and Fe. It was not recognized—at least not early enough in the project—that silica would be

the main component, and Cr, Fe and Ni the main contaminants. With these constituents dominating the immobilization problem, a glass waste form seems natural. Developing a new glass waste form may be superfluous: one of the existing waste form glasses may well suffice.

If the regulatory administrative hurdles are not too burdensome, the MSO/SR mineral residues might be accepted by a facility already equipped to make glassy waste form. Otherwise, a small melting system, with suitable offgas controls, could be constructed based on designs developed elsewhere.

The Synroc concept of a multi-phase polycrystalline ceramic remains valid for MSO/SR mineral residues arising from high-ash waste streams. On the basis of ETDP Final Forms' experience, development of a zircon-zirconolite-perovskite-spinel ceramic waste form is recommended. Processing would be as suggested in Section 3. The alternative glass waste form is worth considering but may require separate development

References

1. ETDP electronic file archive, CD-ROM, created by G. T. Soto, available from M. Hussey. In preparation.
2. Monthly reports, 10/98 – 4/99: (M. G. Adamson and M. W. Hussey, "Expedited Technology Demonstration Monthly Report/PTS Input.") Also in Ref. 1. See also Ref. 11 below.
3. ETDP Final Forms Final Report, Addendum 1, Ceramic Final Waste Form Microstructure. In Ref. 1 as the file "FFM FinalRptAdd2 Microstructure."
4. ETDP Final Forms Final Report, Addendum 2, System Photographs. In Ref. 1 as the file "FFM FinalRptAdd1 SystemPhotos."
5. Peter C. Hsu, Martyn G. Adamson, David L. Hipple, and Robert W. Hopper, "FY98 Final Report for the Expedited Technology Demonstration Project: Demonstration Test Results for the Integrated MSO Waste Treatment System" (11/99).
6. P. C. Hsu, D. L. Hipple, D. V. Squire, E. H. von Holtz, R. W. Hopper & M. G. Adamson, "Integrated Demonstration of Molten Salt Oxidation with Salt Recycle for Mixed Waste Treatment," *WM '98 Proceedings*. Proceedings of the conference WM '98, "HLW, LLW, Mixed Wastes and Environmental Restoration—Working Towards a Cleaner Environment," Tucson, March 1998. Published in CD-ROM format by WM Symposia, Inc. (Tucson, 1998).
7. Operational Safety Procedure 292.19, "ETDP Final Forms System Operation" (effective 12/98).
8. A. E. Ringwood, S. E. Kesson, K. D. Reeve, D. M. Levins & E. J. Ramm, "Synroc" in *Radioactive Waste Forms for the Future* (W. Lutze & R. C. Ewing, eds.), North-Holland 1988.

9. R. A. Van Konynenburg, R. W. Hopper, J. A. Rard, F. J. Ryerson, D. L. Phinney, L. D. Hutcheon & P. G. Curtis, "Ceramic Waste Form for Residues from Molten Salt Oxidation of Mixed Waste," in *Scientific Basis for Nuclear Waste Management XIX*, edited by Dieter Knecht & William M. Murphy (Materials Research Society, Symposium Proceedings 412, Pittsburgh, 1996) pp. 321-328.
10. R. W. Hopper, "Final Forms PTS Input": Monthly memoranda, the content of which was often condensed in editing, providing to Refs. 2 above. Available in Ref. 1 above.
11. R. A. Van Konynenburg, private communication, April 1999.

Acknowledgements: Final Forms has existed in one form or another since 1992. The teams assembled have always be supportive. Most of the many contributions from my co-workers in MWMF, ETDP, the Chemistry and Materials Science Department and Plant Engineering cannot be itemized but are gratefully recognized. Viginia Oversby was a critical driving force early in the project. The continual support and tolerance of my project supervisors—Ron Streit, Joel Bowers and Martyn Adamson—was always appreciated. Paul Densley gave valued ceramics advice. Most of the early laboratory work was ably done by Paul Curtis. Installation and startup of the Final Forms system was greatly facilitated by the professionalism of Greg Soto and Tim Ford. Much of the stressful laboratory work of the past year was done by Fred Miller. Rich Van Konynenburg has remained a valuable source of advice and moral support. To all these I am grateful.

ETDP Final Report Final Forms
Addendum 1
Ceramic Waste Form Microstructure



Microstructure of a typical experimental ceramic waste form.

The white equiaxed grains are zirconolite; the light-gray equiaxed grains are perovskite; the darker-gray elongated grains are spinel; and the darkest gray regions are nepheline. Rutile is not visible, and porosity is black. This specimen was sintered for at 1150°C for 24 h to coarsen the structure for characterization purposes. Grain size for normal (1-h) sintering is smaller, but the structure is otherwise similar. Size bar on the left is 30 μm . See discussion at Fig. 9, Ref. 7.

Note: This figure first appeared in Ref. 7, but the digitized version was of very poor quality.

**ETDP Final Report Final Forms
Addendum 2**

Photographs of the Final Forms Facility

List of Figures

1. Batching system.
2. Attritor.
3. Calciner overview.
4. Calciner inlet detail.
5. Pellet press, granulator, etc.; exit end of calciner.
6. Pellet press, detail.
7. Tube furnaces, entrance end, offgas sparger.
8. Tube furnaces, closed end.
9. Interior of small tube furnace, T~1000°C.
10. Process monitor computer display

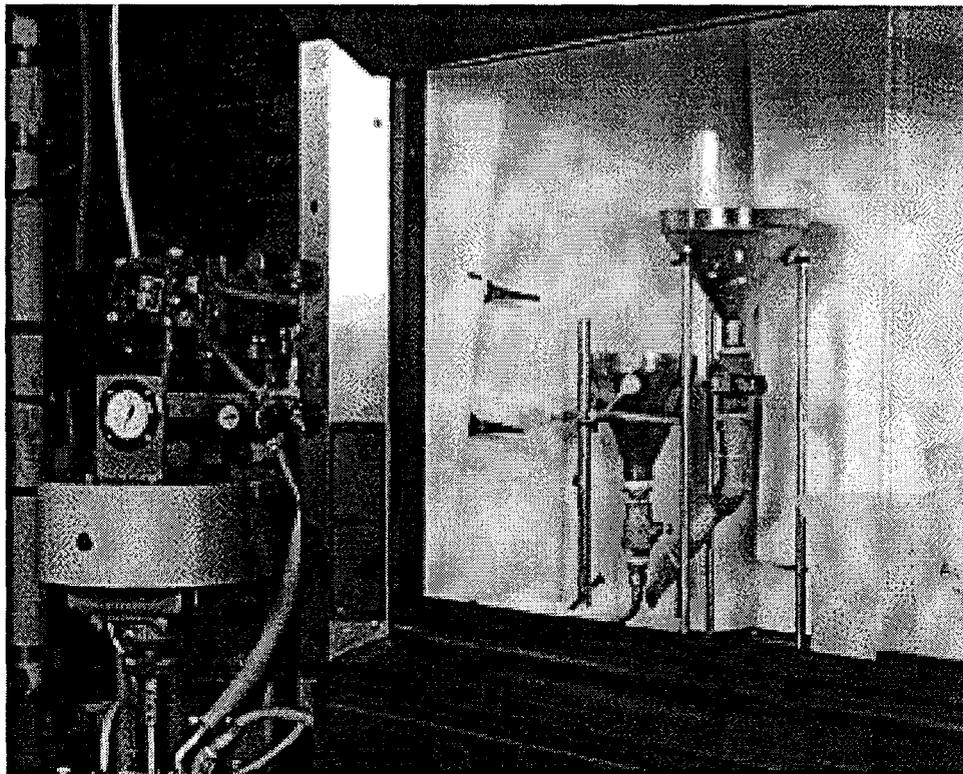


Figure 1. Batching system.

Ceramic formulations are batched in this fume hood and transferred *via* the funnels directly to the attritor on the left. The large funnel is used to convey dry powders; the smaller one is for liquids and slurries. Not visible are two balances in the right side of the hood for weighing residues and reagents.

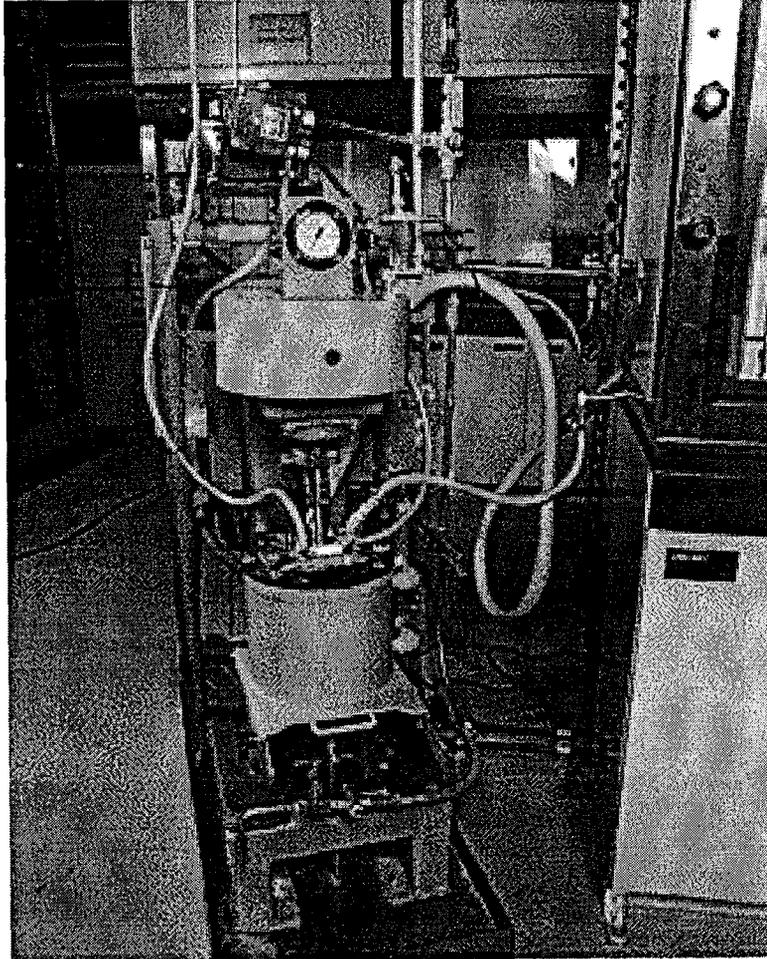


Figure 2. Attritor.

A peristaltic pump (above the tachometer dial) recirculates the slurry during milling. The ball valve at the upper right diverts the flow to the calciner.

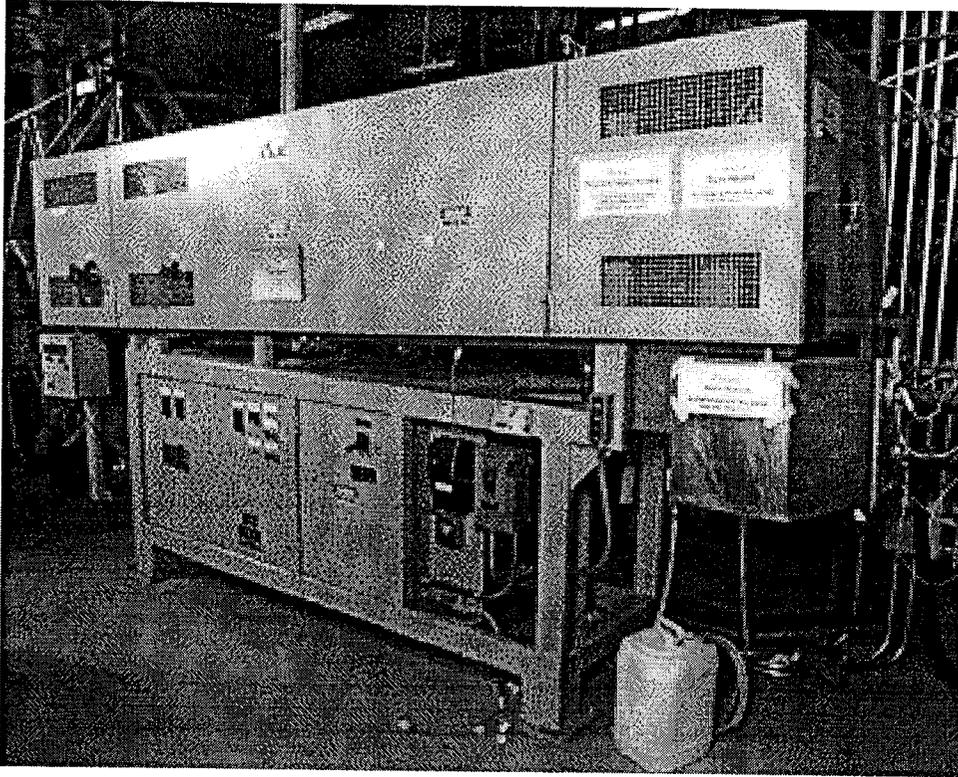


Figure 3. Calciner overview.

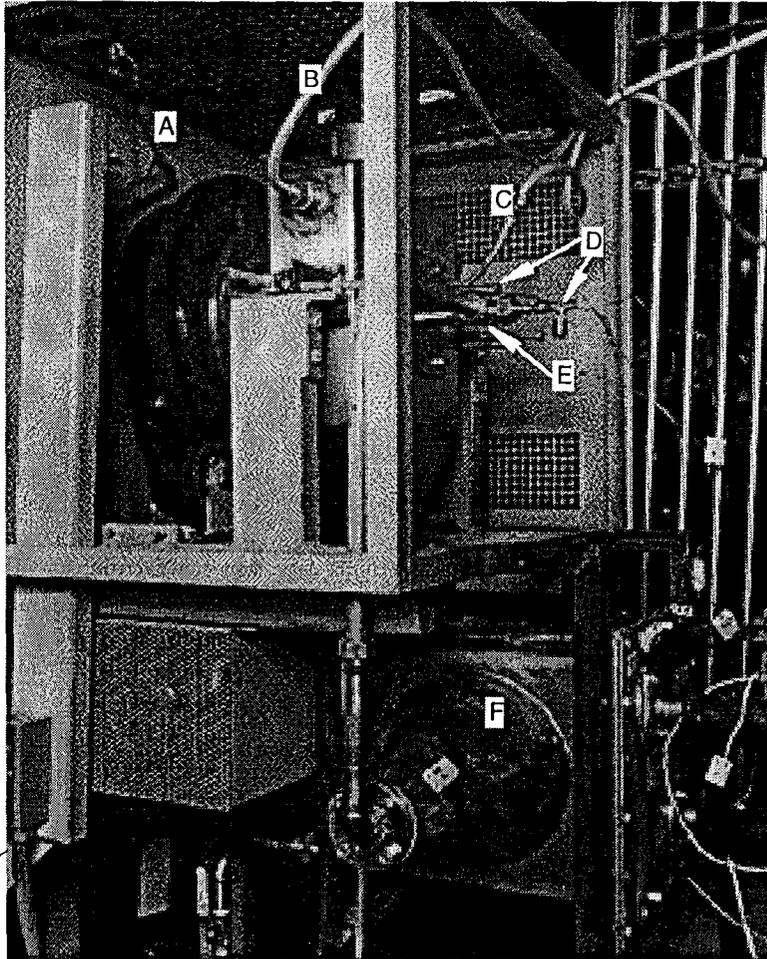


Figure 4. Calciner inlet detail.

- (a) Hammer to knock loose caking in the process tube. Shown in disabled position.
- (b) Tube to monitor negative interior pressure. Safety features are activated automatically if the pressure becomes positive.
- (c) Slurry feed line.
- (d) Thermocouple tubes to measure temperatures inside the process tube (upper arrow) and inside the POG offtake tube.
- (e) Process offgas offtake line.
- (f) POG condenser. Dry POG is released through HEPA filters.

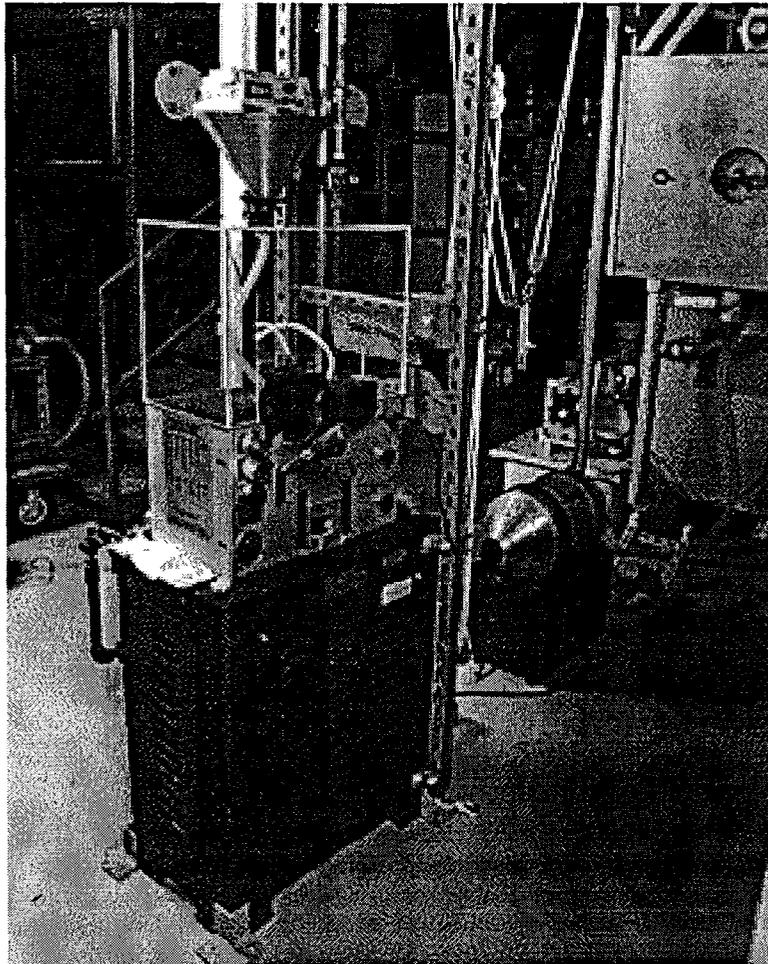


Figure 5. Pellet press, granulator, etc.; exit end of calciner.
The granulator is the conical-cylindrical vessel, shown resting on its roller mill. It is repositioned when being filled with calcine *via* the hose connecting it to the calciner outlet. After granulation, the granulator is again repositioned (suspended from the rope-and-pulley system visible) to feed powder directly into the pellet press.

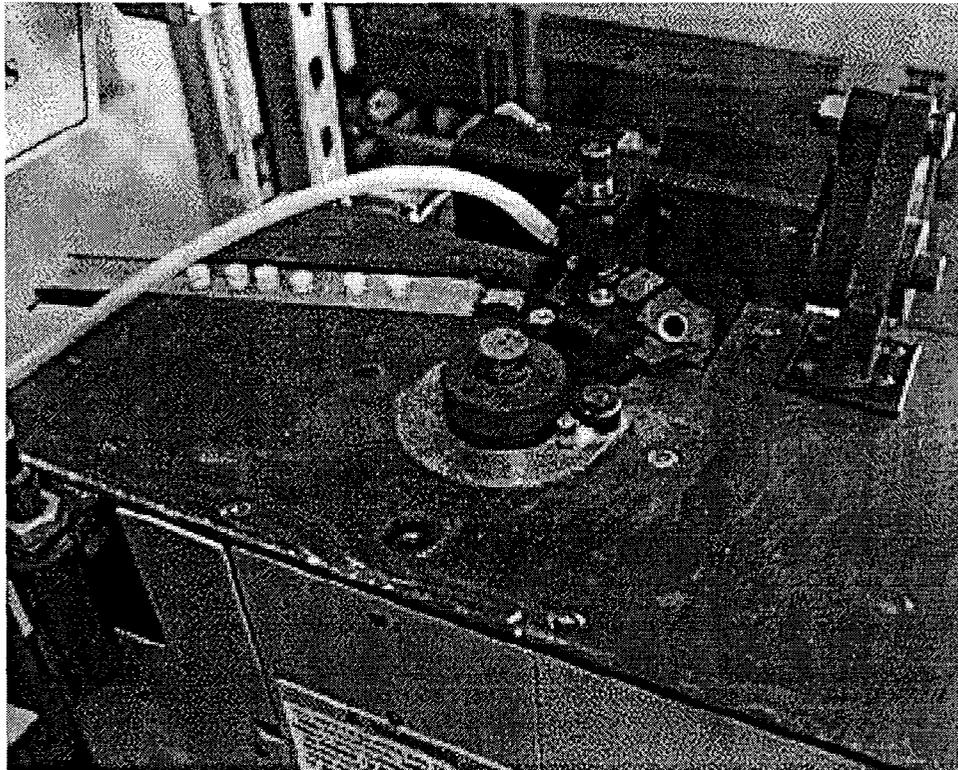


Figure 6. Pellet press, detail.

The hose at the left provides the vacuum to the sliding anvil for the pellet pickup. Powder is fed *via* a rubber hose (removed) into the tube on the right side of the anvil. The anvil is shown in the eject position. The conveyor is not usually used: after ejection, pellets are dropped into the hole to the right of the small conveyor belt, and pass into a closed container.

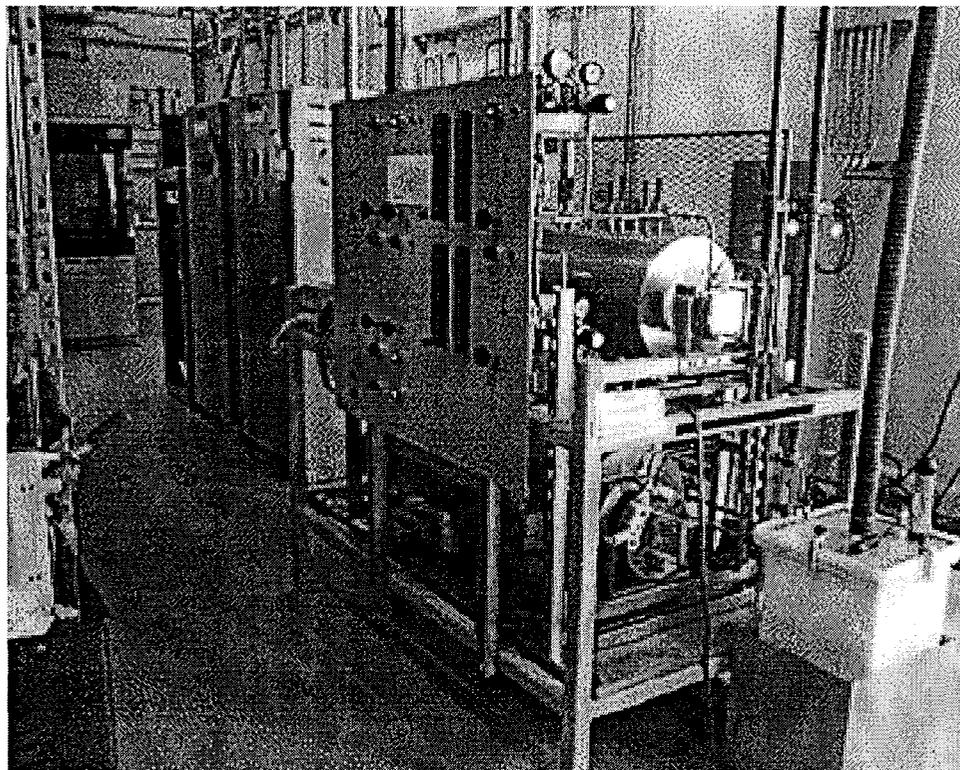


Figure 7. Tube furnaces, entrance end.

Process-air/process-offgas control panel is affixed to the furnace stand. In the background are the furnace control systems, which also contain the power supplies. The white vessel at the lower right is the sparger for the offgas. The pellet press is visible at left.

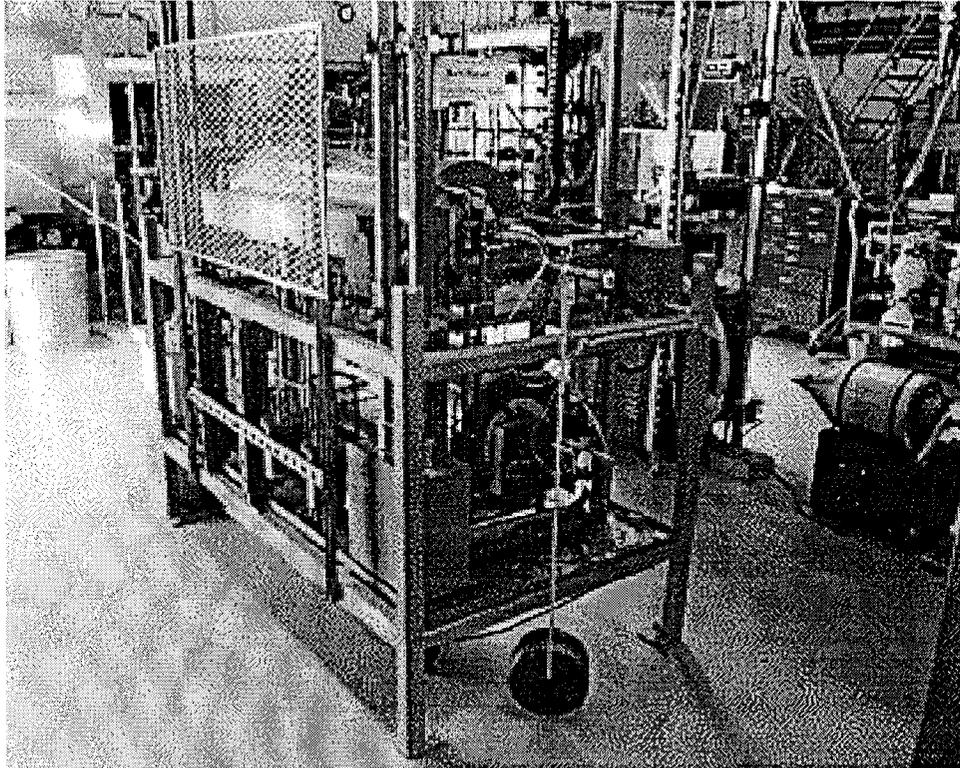


Figure 8. Tube furnaces, closed end.

The process-air/process-offgas system is shown. Pellet press and granulator are visible in the distance. The weights provide a torque to the retort of the small furnace, intended to reduce creep.

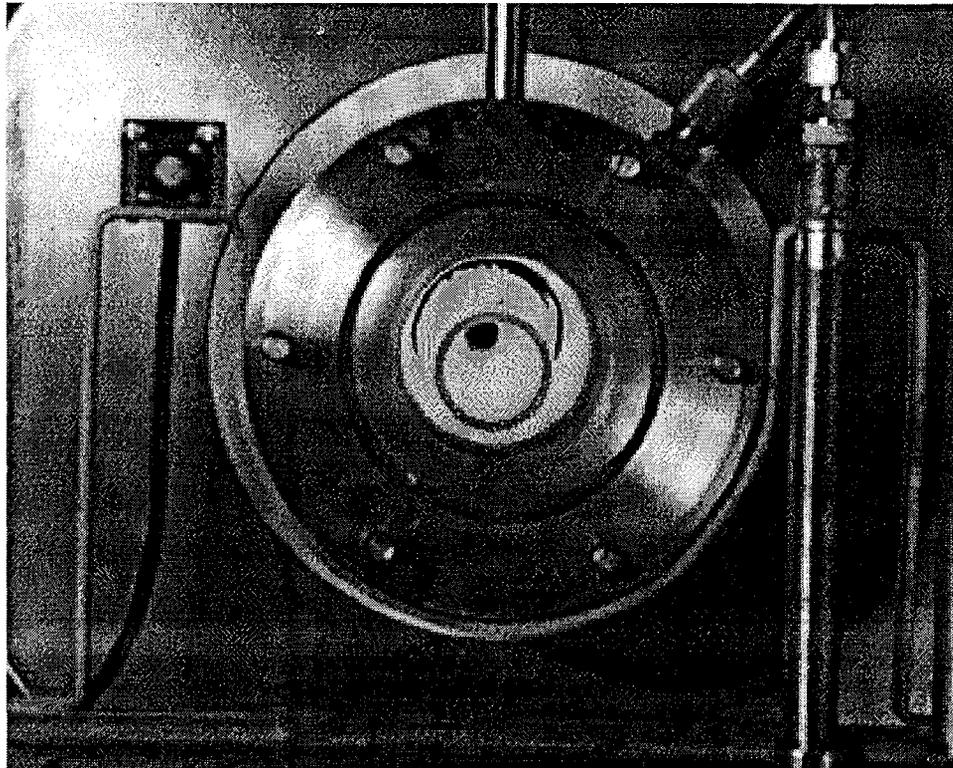


Figure 9. Interior of small tube furnace, T~1000°C.

Sintered ceramic pellets can be seen lying in the inner tube. Photographed during the cool-down stage. The furnace is normally sealed, and typical sintering temperatures are 1150-1210°C.

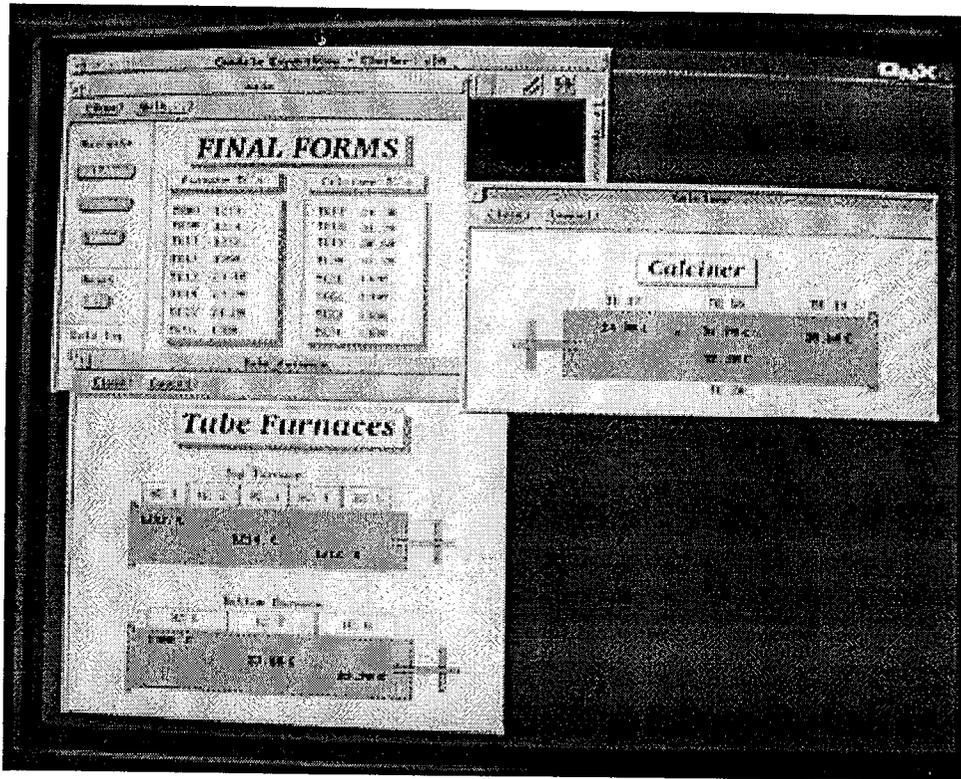


Figure 10. Process monitor computer display.
The charts at the upper left show the temperature readouts of all thermocouples.
The pictoral displays show key process variables.