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DOE/DP/40083-1

AUTOMATED FABRICATION, CHARACTERIZATION AND TRANSPORT OF ICF PELLETS

**FINAL REPORT
FOR THE PERIOD
1 MARCH 1979 - 31 OCTOBER 1980**

**DON W. CLIFFORD, BRUCE A. BOYD, RALPH H. LILIENKAMP
DECEMBER 1980**

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Printed in the United States of America

Available from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price:

Printed Copy \$12.50
Microfiche \$3.50

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for the Period
1 March 1979 - 31 October 1980

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Prepared for the
U.S. Department of Energy
Nevada Operations Office

Under Contract DE AC 08-79 DP 40083

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ABSTRACT

On 1 March 1979, McDonnell Douglas Astronautics Company was awarded a contract, entitled "Automated Fabrication, Characterization, and Transport of ICF Pellets," by the Department of Energy. The contract's long-term objective was to develop a completely-automated ICF reactor fueling system which would produce fuel pellets for less than one cent each.

The near-term objectives of the contract were threefold: (1) evaluate techniques for the production of frozen hydrogen microspheres and demonstrate concepts for coating them, (2) develop and demonstrate an optical characterization system which could lead to automated pellet inspection, and (3) develop and demonstrate a preliminary electrostatic pellet transport control system.

This report describes the equipment assembled for these experiments and the results obtained. The most positive finding was that the coarse diffraction pattern analysis method of pellet characterization shows good promise as an automatic inspection technique. Other optical techniques also showed promise for both long-term and near-term pellet inspection. Two pellet generators were built and evaluated. Frozen argon pellets were produced with both generators. Several coating concepts were evaluated and several systems were designed to meet changes made in the program direction. No coating experiments were actually conducted, however, due to hardware problems with the cryogenic pellet generators, and because of a change in program direction in the last phase of the effort.

Studies of several candidate electrostatic transport control concepts revealed that a multiple-sensor, computerized control system was the best approach. A system was designed and fabricated, borrowing from the design of the Lawrence Livermore Laboratory Baseball II fueling system. As a result of revised priorities, the task was terminated before assembly and operation were begun.

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1.0 INTRODUCTION

On 1 March 1979, the McDonnell Douglas Astronautics Company (MDAC), a division of the McDonnell Douglas Corporation (MDC), was awarded a contract by the Department of Energy (DOE), entitled "Automated Fabrication, Characterization and Transport of ICF Pellets." This contract was awarded, along with several others to industry, for the purpose of applying the results of inertial fusion research from the national Weapons Laboratories in the U.S. to the long-range problems of inertial fusion power reactors for peaceful energy production.

A unique feature of the MDAC effort was that it was largely hardware oriented. MDAC provided the hardware and equipment for an experimental investigation, and the experimentation was accomplished with contract funding. The intent of the program was to evaluate several unique and, for the most part, untried approaches to the reactor fueling problem. These approaches, if successful, could result in extremely low-cost fuel for an inertial fusion reactor.

Glass and organic microspheres filled with DT gas and coated externally with various Hi-Z/Low-Z materials are presently being used as fuel pellets for ICF research and demonstration purposes. These fuel pellets are produced by a multistep process, and are then optically or radiographically characterized on a one-at-a-time manual basis. This approach is unacceptable for useful energy production because such a pellet production and characterization process is prohibitively expensive. Estimates for a pellet factory based on present technology range as high as $\$5 \times 10^8$ leading to a cost of almost 25 cents per pellet. In order for ICF power to be competitive, pellet costs of five cents or lower must be achieved.¹

The long-term objective of the MDAC program was to develop a completely automated ICF reactor fueling system which would reduce pellet production costs by 90 percent, resulting in a pellet cost of less than one cent each. The intermediate objective was to produce individual, well-characterized, high-gain fuel pellets incorporating appropriate coatings and positioning provisions for a NOVA-type experiment by 1985. The near-term objectives and the major tasks of the immediate program were to:

- o Evaluate equipment and techniques for the production of frozen hydrogen microspheres of acceptable size, shape and quality for use as ICF fuel, and demonstrate concepts for coating frozen fuel pellets with Hi-Z materials for improved gain and performance.
- o Develop and demonstrate an optical characterization system based upon existing aerospace technology which could lead to an automated process of pellet inspection and characterization, and utilize the system to fully characterize candidate pellet concepts.
- o Develop and demonstrate a preliminary electrostatic pellet transport control system which will allow automated movement and positioning of candidate fuel pellets during the production process.

These tasks each employed unique approaches to the reactor fueling problem which were designed to be completely automated and yet to ultimately provide a continuous stream of 20 or more fuel pellets per second (over two million per day), all well characterized and controlled to quality specifications, arriving at the target injection point at the proper time and with the proper velocity. The concept is illustrated schematically in Figure 1.

This final report presents the results of the contracted effort which was initially funded for one year. Good progress was made toward the objectives of evaluating the techniques and approaches originally proposed for the

FIGURE 1 – CRYOGENIC ABLATOR-PUSHER IF REACTOR FUELING CONCEPT

fig. 1

program. It should be noted, however, that the program was formulated as a continuing long-term effort and the intent was not to provide complete answers in this initial effort. It was hoped, however, that sufficient data would be produced in the first year to show feasibility and promise where present or, conversely, to demonstrate if unacceptable limitations were inherently present in any of the approaches.

Due to a change in emphasis and funding procedures within DOE, it was not possible to continue the program beyond the first funding period. It was possible within that time, however, to demonstrate that the automated characterization approach involving coarse diffraction pattern analysis holds good promise as an automatic quality inspection technique. Other optical techniques investigated also showed promise for application to both long-term and near-term pellet inspection problems.

Although the automatic fabrication and transport tasks were not carried far enough to determine their ultimate usefulness, a significant amount of hardware was designed and developed to the point of demonstrating that the basic tools are available for additional in-depth studies of several techniques, including those originally proposed, as well as attractive alternatives which were developed during the performance of the contract.

The work reported herein was performed by the Engineering Physics Laboratories of the McDonnell Douglas Astronautics Company in St. Louis, Missouri during the period 1 March 1979 through 1 October 1980.

2.0 EXECUTIVE SUMMARY

The objective of this program was to demonstrate techniques for producing, characterizing, and transporting pure cryogenic fuel pellets to an inertial confinement fusion reactor. A second objective was to determine the potentials and limitations of each technique.

Fuel pellet production is now an expensive and painstaking process including manual tasks conducted on an individual pellet basis. The production process must be simplified to reduce fuel costs to the point where inertial confinement fusion can be economically feasible. A pure cryogenic fuel pellet offers the possibility of low-cost production, small tritium inventories, the high density of frozen fuel which may be necessary to obtain high yield, and the elimination of extraneous materials.

To meet the program objectives, the program was divided into three tasks. These three tasks were pellet fabrication, pellet characterization, and pellet transportation. While these tasks were related to each other, each of them could progress independently during the early months of the program. Later in the program, it was planned to marry the three tasks to provide a combined system demonstrating each of the desired objectives.

The pellet fabrication part of the program was to build on the work of Drs. Charles Hendricks and Robert Turnbull. In their work at the University of Illinois, they directed a number of experimental studies in the production of frozen hydrogen microspheres. They produced both solid and hollow spheres of frozen hydrogen a few hundred microns in diameter, the size range of interest for fuel pellets. A cryopellet generator based on their design could be used to study the production of cryopellets and to provide cryopellets for coating experiments. The coating experiments would evaluate methods to apply inert gas coatings on the frozen deuterium-tritium fuel. These coatings would

serve as the ablator and the pusher-tamper. For the coating experiments, nitrogen cryopellets were to be coated with argon.

Cryopellet production using a frozen stream of hydrogen isotope droplets show great promise as a method of mass-producing low-cost targets for energy-producing inertial confinement fusion reactors. Certainly, some such technique must be made to work in order to obtain the high volume of targets required for a reactor (two million per day). Cryopellets offer a combination of advantages, including high energy gain, low cost, and adaptability to computerized automation necessary to make inertial confinement economically viable.

A cryopellet generator based on the University of Illinois design was built at MDAC. After overcoming a great number of persistent operational problems, the generator finally produced argon cryopellets. However, every attempt to produce hydrogen cryopellets failed. The principal source of the problem was insufficient cooling by the heat exchangers used to liquify the hydrogen. A new cryopellet generator was built to an original MDAC design. This generator incorporated a new heat exchanger concept and was fabricated entirely of glass. This system allowed good visual observations of the processes and good liquification of hydrogen. Again argon cryopellets were produced, but the heat transfer into the nozzle was too great to produce a good stream of uniform hydrogen pellets. There was no problem in producing the liquid hydrogen, but before the task could be pursued to completion, it was cancelled by the DOE to divert the funds to Task 2.

A cryopellet coater was designed to use the original U. of I. generator and the transport system described in Task 3. The design was modified several times initially, in an effort to eliminate the dependence on the transport system. The design was later modified to incorporate alternate coating concepts. The final design change was required when the new cryopellet generator was

introduced to the program. Several detail drawings were produced and some components were fabricated before Task 1 was curtailed. Despite the curtailment of Task 1, the progress that was made indicated that the pure frozen fuel pellet approach has the best potential for IF reactor fueling.

The pellet characterization part of the program was to develop and evaluate three optical techniques. The three techniques were photomicrography, coarse diffraction pattern analysis, and Airy disk measurements. The pellet characteristics of major interest were the pellet sphericity, the pellet radius (both inside and outside if hollow), and the aspect ratio of hollow pellets.

To a lesser extent, other characteristics such as mass, surface roughness, number density, and speed of moving pellets were of interest. Each of the techniques was to be computer-compatible so that an automated inspection system could be developed. An automated inspection system is essential to produce low-cost fuel pellets.

Good success was realized on this task. A photomicrography system was demonstrated which used a solid-state video camera to record the pellet image and to provide gray-scale encoding for input to an on-line microcomputer. Image processing algorithms were developed to accurately extract the pellet dimensional parameters. The system was used to optically characterize moving cryopellets produced by the pellet generator.

A second characterization system was used to demonstrate both the coarse diffraction pattern analysis and Airy disk approaches. Coherent light generates Fraunhofer diffraction patterns in the far field. The patterns were recorded on photographic film and by the solid-state camera and by a special ring/wedge detector. An extensive recognition computer program was procured and implemented to assist in the analysis of the data obtained with the ring/wedge detector. It was determined that the diffraction patterns of imperfect

pellets could be readily distinguished from those of good pellets. The quantitative limitations of the technique were not determined.

The pellet transportation part of the program involved the development of an electrostatic pellet motion control system. The pellet transportation system involved four steps. The first was to produce a charge on the pellet. The second step was to measure the charge on the pellet or the charge-to-mass ratio of the pellet. The third step was to determine the pellet trajectory, velocity, and position. The last step was to control the trajectory of the pellet.

A prototype transport and control system was designed, based on the Lawrence-Livermore Laboratories (LLL) Baseball II fuel injector. This system included a droplet charging assembly, a gating assembly, a tracking unit, a computer interface, and a microcomputer. Fabrication was begun on the components for this system, and a number of them were completed before this work was terminated as a result of a change in the program requirements.

The MDAC program was structured as a hardware oriented experimental program which was expected to continue for a number of years. Consequently, much of the early effort was expended in assembling and developing a large assemblage of sophisticated equipment. The equipment was procured with MDAC capital funds. Because of the hardware start-up delays, the sudden termination of the original intent of the DOE PDRA program prevented some of the technical objectives from being met.

3.0 FUEL PELLET PRODUCTION

The mass production of low-cost fuel for inertial confinement fusion is essential to making fusion reactors economically feasible. One possible approach to mass producing low-cost fuel pellets is the cryopellet generator. In this approach, a steady stream of droplets of liquid fuel is formed and then frozen. The frozen pellet may be either solid or hollow. The frozen pellet is then coated, first with a condensible Hi-Z material to serve as the pusher-tamper, and then with a Low-Z material to serve as the ablator.

The work of Drs. Charles Hendricks and Robert Turnbull at the University of Illinois was used as the starting point in the pellet fabrication. They produced both solid and hollow spheres of frozen hydrogen a few hundred microns in diameter. A cryopellet generator based on their design was built to evaluate the potential and limitations of this method and to provide a supply of cryopellets for coating experiments.

3.1 CRYOGENIC COATING CONCEPT

3.1.1 Cluster Beam Coater - The initial coating concept proposed for this program was to pass hydrogen pellets through a xenon cluster beam. Each cluster was to be a microscopic group of xenon molecules in the liquid or solid state. Clusters colliding with the pellet were assumed to attach themselves to the pellet. The advantage of the cluster beam approach was that the coating gas was already condensed and would not, therefore, have to give up its heat of fusion to the cryopellet. Thus, the chances of melting the low heat capacity pellet were reduced. McDonnell Douglas Astronautics Company proposed that this technique be evaluated by passing nitrogen pellets through an argon cluster beam. This proposal was based on the concept that nitrogen pellets would be easier to produce and less expensive since liquid helium

would not be required. The use of argon rather than xenon was also based on cost.

3.1.2 Test Validity - During the contract kickoff meeting in St. Louis, 7-8 February 1979, a question was raised about the advisability of conducting cryogenic pellet coating studies on frozen nitrogen droplets when the eventual application would be to frozen hydrogen droplets. The following analysis was conducted in response to that question.

Three thermodynamic models are considered: (1) xenon on hydrogen, (2) argon on nitrogen, and (3) argon on hydrogen. Table 1 presents physical and thermal properties of the four gases considered for this experiment.

TABLE 1 - PHYSICAL AND THERMAL PROPERTIES OF SELECTED GASES

PHYSICAL PROPERTIES	HYDROGEN	NITROGEN	ARGON	XEXON
MOLECULAR WEIGHT	2.0157	28.016	39.3944	131.30
NORMAL BOILING POINT (K)	20.268	77.35	87.29	165.02
TRIPLE POINT TEMPERATURE (K)	13.803	63.15	83.80	161.37
TRIPLE POINT PRESSURE (TORR)	52.82	94.24	515.66	611.8
HEAT OF VAPORIZATION (CAL/G)	107.0	47.6	38.9	23.0
HEAT OF FUSION (CAL/G)	13.9	6.1	6.7	3.3
DENSITY SOLID (KG/M ³)	86.64	9.47×10^2	1.6×10^3	—

GP79-9668-21

Cooling a gram-mole of xenon from liquid at the triple point to 13K requires removal of 1392 calories, including the 433 calories necessary for the change of phase. The heat removed from the coating gas will be transferred to the pellets, causing an increase in temperature. The rate of heat transfer in the pellet, the mass of the pellet, the mass of the cluster, and the rate of pellet-cluster collisions will all affect the success of the coating process. It is expected that much of the heat from the pellet will cause

sublimation of hydrogen from the pellet in the vicinity of the collisions.

The heat of sublimation, taken here as the sum of the heat of fusion and the heat of vaporization, is about 243 cal/gram-mole for hydrogen. Therefore, six to seven hydrogen molecules must be sublimated for each xenon molecule in the cluster. Some improvement in this ratio could be achieved by lowering the temperature of the cluster by evaporation or sublimation.

Cooling liquid argon from its triple point to the nitrogen triple point requires the removal of 401 cal/g mol, including 246 cal/g mol necessary for the change of phase. The heat of sublimation for nitrogen is 1504 cal/g mol. This appears to be an easier problem than coating hydrogen pellets with xenon.

Coating hydrogen pellets with argon may be almost as difficult as coating with xenon. The heat removal required to cool liquid argon from its triple point to 13K is about 642 cal/g mol, including 246 cal/g mol for the phase change.

While there is no rigorous theory to predict cluster growth and formation, there are similar relations between beam parameters. These similar relations can be used to predict the outcome of similar experiments from the results of one experiment. The model of "corresponding jets" is an exact relation to correlate experiments with different gases. This model depends on only two gas-specific parameters: (1) the characteristic energy and (2) the characteristic length. The rare gases work very well in this model with the exception of helium where quantum-mechanical deviations have to be taken into account.

The coating of a pellet presents many problems besides the thermodynamic problem discussed in the preceding paragraphs. Consider what must occur to produce a coated pellet. First, a hollow liquid sphere must be formed. This occurs near the triple point (13.8K and 52.8 torr for hydrogen). The sphere is frozen by lowering the pressure and evaporating or sublimating some of the

hydrogen. A number of vacuum stages, each with its own pumping system and connected regions, are required. The pellet must be guided through each of these orifices. After freezing, the pellet must be accelerated and injected into the coating chamber. Again, the pellet will move through a number of vacuum stages, since the pressure in the coating region may be higher than that of the freezing chamber. After coating, the pellet will move through additional vacuum stages to maintain the pellet in a frozen state and then enter the characterization system. From this description of the process, one can see the complexity of the coating system. Another uncertainty of this approach is the uniformity of the coating and its transparency. Significant hardware development is anticipated before a workable coater is produced.

The thermodynamic analysis indicates that the development of a coating process will probably require considerable effort to adjust the mass of the hydrogen pellet, the thickness of coating, and the number of coatings applied. However, there are no inherent thermodynamic limitations which rule out the approach. There are critical technology questions which must be answered, however, before the coating process can be pursued in detail. Those questions, which include, besides the mechanical problems, the basic quality of coating which can be achieved with cluster beams, are most logically addressed in the more convenient LN_2 apparatus.

3.1.3 Coater Design Study - Our original concept was to incorporate a convergent-divergent nozzle to produce the supersonic flow necessary to obtain a cluster beam. The pressure and temperature of the coating gas would be controlled. The temperature of the gas leaving the nozzle would be:

$$T = T_0 / [1 + (\frac{\gamma + 1}{2}) M^2]$$

where T_0 is the source temperature
 γ is the ratio of specific heat
 M is the Mach number

The Mach number will be determined by the nozzle geometry as long as the pressure ratio across the nozzle is less than or equal to:

$$\frac{P}{P_0} = \left[1 + \left(\frac{\gamma - 1}{2} \right) M^2 \right]^{-\left(\frac{\gamma}{\gamma - 1} \right)}$$

where P is the downstream pressure and P_0 is the source pressure.

Most molecular beam and cluster beam systems employ a skimmer and a collimator downstream from the nozzle to extract the core of nozzle flow field. If the skimmer is located less than half the distance to the "Mach disk," the flow should be shock-free. The distance to the Mach disk is:

$$x_m = 4.126 \times 10^{-2} S^{1/2} T_0^{1/4} \text{ cm}$$

where S is the pumping speed in liters/sec. The pumping speed required to obtain a reasonable size x_m becomes rather large. The pressure in this region is usually maintained between 0.1 and 0.01 torr. The pressure in the region between the skimmer and the collimator is normally in the 10^{-4} torr range. MDAC did not plan to use a collimator; rather, this region would be the coating chamber. While this pressure is much lower than that normally used for vacuum coating, the pressure in the beam will be much higher. If the pellet can produce enough turbulence, a uniform coating will be obtained.

After a discussion with Dr. Jim Madson and Dr. T. C. Peng of McDonnell Douglas Research Laboratory (MDRL), who both have been working with molecular beams for some time, a simple orifice-type nozzle (sonic nozzle) rather than a convergent-divergent nozzle was recommended. One of the principal reasons for this choice is that Mach number is controlled by the upstream pressure. The Mach number is given by:

$$M = 1.18 (K_{no})^{-\left(\frac{\gamma - 1}{\gamma} \right)} \quad (1)$$

where K_{no} is the Knudson number based on the stagnation mean free path

(λ_o) and the throat diameter (D).

$$K_{no} = \frac{\lambda_o}{D}$$

$$\lambda_o = T/\sqrt{2}\pi n_o \delta^2$$

where n_o is the number of molecules/unit volume and δ is the molecular diameter

$$n_o = P_o/T_o$$

where P_o and T_o are the stagnation pressure and temperature, respectively.

The Mach number increases as a function of distance from the nozzle until it reaches the value given by equation (1).

The Mach disk in this case occurs at a distance x_m from the nozzle given by:

$$x_m/D = 0.67(P_o/P_1)^{1/2}$$

where P_1 is the background pressure.

The mass flow through the orifice (W_{max}) is given by:

$$W_{max} = \frac{\pi D^2}{4} P_o \frac{\gamma m}{RT_o} \left[1 + \left(\frac{\gamma - 1}{2}\right)\right]^{-\frac{(\gamma + 1)}{2(\gamma - 1)}}$$

where m is the molecular weight and R is the universal gas constant.

The stagnation conditions P_o and T_o control the Mach number mass flow and the cluster size for a given nozzle diameter. The distance to the Mach disk is dependent on the downstream pressure and the stagnation pressure. Temperature control will be provided, but T_o should be just above the condensation temperature. The nozzle diameter should be small to limit the mass flow; diameters of 10 to 12.5 μm are being considered. These are commercially available.

Most of the work reported in the literature use high pressures and temperatures. For example, the figures in "Cluster Beams from Nozzle Sources" by Otto F. Hagena² show pressures in the range 10^3 to 10^4 torr and temperatures in the

range 10^2 to 10^3 K. Calculations suggest a pressure range of one to 100 torr and a temperature less than 100 K. The Mach number should be kept low, since some of the excess kinetic energy will be converted to thermal energy when the coating gas becomes part of the pellet. Also, the clusters should be kept small to keep from melting the pellet.

A 10- μ m (0.001 cm) diameter orifice with a source pressure and temperature of 5 torr and 88 K, yield a Mach number of 1.85. The flow rate is 2.82×10^{-7} gm/sec and the through-put is 1.32×10^{-4} torr ℓ /sec (at 300 K). The temperature of the gas for isentropic flow is 41.3 K. In order to obtain a reasonable distance to the Mach disk, the background pressure must be very low, i.e., for a background pressure of 1×10^{-5} torr, the distance to the Mach disk is only 4.7 mm. The pumping speed necessary to maintain the background gas pressure at 10^{-5} torr is 14 ℓ /sec for the coating gas. If this low a pressure can be maintained, a skimmer may not be needed.

Increasing the stagnation pressure to 50 torr increases the Mach number to 4.65, the through-put to 1.32×10^{-3} torr, and the pumping speed to 140 ℓ /sec. The gas temperature is decreased to 10.8 K. The distance to the Mach disk is 1.5 cm.

Decreasing the stagnation pressure to 1.1 torr reduces the Mach number to 1.01. The gas temperature is 65.8 K.

Gas temperatures given for isentropic flow do not take into account condensation. Actual temperatures will be somewhat higher, since some of the thermal energy given up must come from the change of phase.

The preceding calculations are based on the assumption that the flow is compressible. As a comparison, the incompressible flow equations, developed by Lund and Berman,³ were used to calculate the mass flow in the operating region of a coating nozzle. These results are presented in Figure 2. The

Knudsen number is about one at one torr, which indicates that the transition to molecular flow should be near. Based on Figure 2, as long as the upstream pressure is maintained above one torr, the flow will be isentropic.

The cluster size (N) increases with increasing P_0 and with decreasing T_0 . For a constant T_0

$$N \propto P_0^n$$

where the exponent n is dependent on the gas and nozzle.

For a constant N

$$P_0/P_{0,1} = (T_0/T_{0,1})^r (D/D_1)^q$$

Extrapolation of the data presented in Hagena to the conditions proposed for the coating nozzle results in Figures 3, 4, and 5. From Figure 5, it appears that a source pressure of 800 torr at 88K and a 0.01-mm nozzle will produce ten-molecule clusters. This is greater than the pressure proposed. The Mach number for these conditions is 14.1. The gas temperature is significantly lower, so that the velocity is only about one third larger than that with a source pressure of five torr. The gas load on the pumping system is 160 times that with five-torr source pressures, requiring a larger pumping system.

Another approach is to use a larger nozzle. In Figure 5, the line for $D = 0.1$ mm shows that a pressure of 140 torr at 88K should produce ten-molecule clusters. Since the mass flow is proportional to $d^2 P$, the mass flow is 2800 times that of five-torr source with a 0.01-mm nozzle, and 17.5 times that of 800-torr source with a 0.01-mm nozzle. Larger nozzles mean larger pumping systems.

Based upon this study, it is obvious that there are a number of uncertainties which can only be resolved by an experimental program. No data exists

FIGURE 2 — COATING NOZZLE DESIGN CURVES

FIGURE 3 — SOURCE PRESSURE FOR CLUSTER BEAMS VERSUS SONIC NOZZLE DIAMETER

FIGURE 4 — SOURCE PRESSURE VERSUS CLUSTER SIZE

FIGURE 5 — SOURCE PRESSURE VERSUS TEMPERATURE

for the temperature/pressure regimes wherein it will be operating. Therefore, design of the coating system must incorporate flexibility in the range of operating parameters.

3.1.4 Coater-Generator-Freeze Chamber Interfaces - The preliminary design studies of interface between the pellet generator and the coater were begun in March 1979. The concept was to use a number of vacuum chambers, each at a lower pressure and connected with a small orifice or nozzle. The size of the orifice had been tentatively set at ten-pellet diameters. For the triple point condition, it appears that the flow through the orifice will be isentropic. If the flow is sonic or supersonic, undesirable clusters may be formed. Therefore, it will be necessary to limit the pressure reduction in at least the first stage to avoid sonic flow.

The literature applicable to the injection of the pellet into the freezing chamber indicates that the injection system design will have a great effect on pellet dispersion. A method to predict the effects on the pellet has not been found. Even if the system were designed for viscous gas flow, the presence of a pellet could produce some turbulence. Therefore, it does not appear to be worthwhile to try to maintain a viscous flow. It was decided to use an orifice between the triple point chamber and the freezing chamber without an intermediate pressure chamber. The trajectory control system will be designed to override the dispersion of the pellets.

3.1.5 Coater Design. A design layout of the cryopellet coater, shown in Figure 6, locates the coater downstream of the transport system. While some provision will be made to adjust the position of the pellet entrance orifice, the coater is very dependent on the transport system to accurately insert the pellets. The design employs a heat exchanger, like the ones used in the pellet

generator, to cool the argon to near its boiling point. The cold argon gas is then supersonically expanded into the coating region. The supersonic expansion will further cool the argon. Some of this cold argon gas condenses on the nitrogen cryopellet.

FIGURE 6 - COATER DESIGN CONCEPT

GP79-9668-32

3.1.6 Alternate Coating Concepts. During the Department of Energy review meeting on 24 July 1979, concern was expressed by the national laboratory personnel about our program structure which requires the use of the Task 3 transport system to operate the Task 1 coater. In response to that concern, the feasibility of coating pellets without using the transport system was investigated. Because of the expected divergence when the pellets enter the high-vacuum freezing chamber, a design concept has been developed which brings the coater inlet very close to the exit of the drop chamber. This concept is shown in Figure 7. The coater is basically the same as that previously described. The droplet chamber is the same one that was designed for Task 3. With this

FIGURE 7 — CLOSE-COUPLED COATING SYSTEM

arrangement, it would be possible to demonstrate the coater without using the transport system, and also have a coater that is compatible with the transport system when it is available.

Dr. Turnbull was asked to develop an alternative concept for coating which does not use a cluster beam approach. The best alternate coating concept is one in which cold helium gas and the cold coating gas are both introduced into the coating chamber. In this concept, the coating chamber pressure will be much higher than in the cluster beam coater. The cold helium gas will serve as refrigerant for both the pellets and the coating gas. The coating gas will not have to be supersonic to be cooled, and the coating gas will not be confined to a narrow cluster beam. Since the pressure is high, it is possible

that some "wraparound" may occur which could improve the uniformity of the coating. The coating operation is similar in concept to vacuum coating techniques now employed commercially. The coating gas could be considered the evaporation source. The helium would be the inert gas used to control the chamber pressure, as well as the refrigerant.

The coating design was modified to be suitable for experiments using the cluster beam or the alternate coating concept. The modified design, shown in Figure 8, incorporates glass drop chamber, freezing chamber, and inlet-to-coater chamber, all connected by metal bellows, to allow continuous observation of the droplet stream. The control system for the coater is similar to the pellet generator system, as is the heat exchanger design. Vapor pressure thermometers in the heat exchanger control the flow of refrigerants (liquid nitrogen or helium), thus controlling the temperature of the coating or cooling gas. Two small servo motors position the inlet to the coating chamber.

3.1.7 Vertical System - When the switch from a horizontal pellet generator to a vertical generator was made, all coater designs had to be completely revised. To be compatible with the vertical generator, the revised coater designs built upon a six-inch glass cross. The vacuum jacket was eliminated. The heat exchanger for the coating gas and the helium refrigerant gas was located in the glass cross.

Two orifice plates to separate the production, freezing, and coating chambers were fabricated. These plates have orifices which have two degrees of freedom and approximately three cm of travel in both directions. The first one was installed as an entry to the freeze chamber.

3.2 PELLET GENERATOR

3.2.1 Water Droplet Generator - A room temperature water droplet generator was built as a test-bed for evaluating design alternatives which were not

FIGURE 8 — CRYOPELLET COATER ASSEMBLY

temperature dependent. Items evaluated in the water droplet generator included nozzle designs and optical techniques. The generator was used to test the pellet generator setup. A series of tests was conducted to evaluate the effects of pressure and frequency on the size of the droplets. Results of these tests are presented in Figures 9 and 10. In Figure 9, lines of constant droplet size are plotted for frequency versus flow rate; the dashed line is the boundary between stable and unstable droplet streams. In Figure 10, droplet radius versus frequency is plotted for constant flow rates. Figure 11 shows a group of droplets from the water droplet generator.

FIGURE 9 — WATER DROP GENERATOR FREQUENCY vs FLOW RATE

FIGURE 10 — WATER DROP GENERATOR DROP RADIUS vs FREQUENCY

FIGURE 11 – WATER DROPLETS

3.2.2 Cryopellet Generator

a. University of Illinois Generator - Two cryopellet generators were built. The first of these was based on the University of Illinois design. This unit is shown in Figure 12.

During checkout of the cryopellet generator, argon was used in place of hydrogen; liquid nitrogen was used as the refrigerant in place of liquid helium. A number of problems were discovered and the pellet generator was modified to correct these problems. The greatest problems experienced were with leaks in the regulators which control the pressure and temperature of the argon and the pressure of the droplet chamber.

New regulators were installed, and although some improvement in regulation was observed, the regulators continued to experience leaks. The regulators did not control until there was sufficient flow through them to overcome leakage, even with soft seats. This leakage was not a problem when the system was running, but did make startup more difficult. Leakage problems in both vacuum regulators used to control the flow of refrigerant (liquid nitrogen) through

FIGURE 12 — PELLET GENERATOR AND VIDEO PHOTOMICROGRAPHY SYSTEM

the heat exchanger were experienced. The leakage was between the reference pressure and vapor pressure thermometer sides of the regulator. This leakage allowed nitrogen gas to get into the thermometer, resulting in false temperature indications and freeze up.

Several runs were aborted as a result of blocked or clogged nozzles. The system had to be dismantled each time and the system cleaned and back-flushed. The system would operate longer each time before the nozzle clogged again. After several cycles, the system began to deliver a solid continuous jet. This type of break-in-cycle had been experienced at the University of Illinois and appeared to be typical. Another form of blocked nozzle was determined to be caused by freezing moisture in the argon. This was overcome by running the argon feed gas through a cold trap to remove moisture.

There were also a number of leaks in the droplet chamber, particularly around the windows and through the electrical feed-throughs. The Illinois system also experienced problems with vacuum leaks due to wide temperature fluctuations between room temperature and the operating temperature. An improved droplet chamber design was therefore implemented using thicker windows for greater sealing pressure and ceramic-to-metal feed-throughs to replace the epoxy potting.

Another problem was the accumulation of liquid argon in the drop chamber to the point that the jet was completely submerged. This may be a problem with argon that might not exist with hydrogen. This problem was overcome by installing a heater on the drop chamber to evaporate liquid argon accumulations.

As a result of eliminating these problems, the system began to operate much more reliably. However, some instabilities in the jet and drop formation were still observed which appeared to be caused by an oscillation of the drop chamber pressure. Two additional modifications were made to the control system which further improved the stability of the drop chamber pressure. First, the reference pressure system was opened to atmospheric pressure, which eliminated the oscillations in the reference pressure. Second, a large volume was added to the drop chamber vacuum system.

A number of repeatable runs were made using argon drops, and the system ran for hours without problems. Stable operation of the pellet generator with liquid argon droplets is shown in Figure 13. Figure 13 is a closeup of the CRT screen showing the droplets forming as the jet breaks up. The field-of-view covers a distance of about six mm from the tip of the nozzle. Note that oscillations in droplet geometry have essentially damped out over that distance. The photomicrography system used for the display will be discussed in Section 4.1.

FIGURE 13 — TELEVISION PICTURE OF CRYOGENIC ARGON DROPS

When the first attempt was made to produce liquid hydrogen droplets, the system was unable to cool down to the point where hydrogen liquefaction occurs, which naturally precluded jet formation. One possible cause was insufficient liquid helium flow resulting from a line obstruction or insufficient line size. Measurement of the pressure drop across the heat exchangers during gas flow at room temperature revealed significant flow restrictions in both heat exchangers. An attempt was made to enlarge the flow channels in the exchangers by pumping ammonia persulfide, a copper etching solution, through them. This had negligible effect on helium flow, however. The pressure measurements in the heat exchangers indicated that the 1/8-inch lines to and from the heat exchanger were too small. It was also determined that the flow rate for the two heat exchangers were significantly different. Since the supply line was common most of the way, it was cut between the point of branching and

the inlet to the heat exchanger. Reverse flow through the system dislodged copper shot which was in the tubing, causing the low flow rate. The tube was replaced with 1/4-inch lines and the generator reassembled. In addition, quarter-inch ball valves were installed in the helium exhaust lines immediately after the heat exchangers to vent the exhaust into the atmosphere. These valves bypass the flow restriction through the control system during cool down. With these modifications, the time required to produce a liquid argon jet, using liquid nitrogen as the refrigerant, was reduced from over one half hour to five minutes.

The loose copper shot found in the lines to the heat exchanger caused doubt about the sintering process used when the heat exchangers were fabricated. When the heat exchanger problem was discovered, the decision was made that the total system complexity and nonreliability did not warrant additional development work on that design concept.

b. MDAC Generator - Experiments were conducted to evaluate alternate generator concepts with the potential for enhanced flow stability. Reasonable success was realized with a heat exchanger made of 1/4- and 1/8-inch copper tubing coiled together around and soldered to a two-inch solid copper cylinder. A vapor pressure thermometer was located in the copper cylinder. Liquid argon was produced, using liquid nitrogen as the refrigerant, but good temperature measurements were not obtainable. From these results, the design shown in Figure 14 was developed. This design again used the two coils soldered to a cylinder as the main heat exchanger. The heat exchanger was surrounded by another cylinder and the exhaust refrigerant used as a thermal shield for the heat exchanger. The condensed gas was collected inside the heat exchanger cylinder. Phase separation can take place in this volume if necessary.

FIGURE 14 – COILED TUBING HEAT EXCHANGER DESIGN

A heat exchanger of the design described in the preceding paragraph was built and evaluated. Initial testing was with argon gas and liquid nitrogen. Tests were done at atmospheric conditions; then the heat exchanger was mounted into a vertical glass pipe vacuum system. The atmospheric test demonstrated that liquid argon could more easily be produced with this heat exchanger design. It also demonstrated that the argon could be frozen if the nitrogen flow was too large and liquid nitrogen accumulated in the outer cylinder.

The original pellet generator was removed from its metal horizontal vacuum system and installed in a vertical glass pipe vacuum system. This change provided the opportunity to evaluate two possible advantages. The first was to avoid the gravity effects on the pellet's trajectory. The U. of I. system was constructed on a horizontal axis to facilitate fueling experiments on a fusion device. A vertical axis was more desirable for the MDAC experiments. The second advantage was to eliminate the complexity of the guard vacuum system. To check this second concept, the entire system was operated at the pellet chamber pressure, i.e., 500 to 600 torr.

The second cryopellet generator was designed using the results obtained in these previous experiments. A new heat exchanger assembly was installed in a new generator assembly (Figure 15). The heat exchanger (Figures 16 and 17)

FIGURE 15 — CRYOGENIC TARGET TEST SETUP

FIGURE 16 — HEAT EXCHANGER CROSS SECTION

was constructed of pyrex glass. In operation, hydrogen passed through the central coil which was immersed in a liquid helium bath. The hydrogen partially liquified and exited the reservoir in a two-phase flow. Phase separation occurred through a sintered glass filter located in the head space of the liquid hydrogen reservoir which was located directly below the helium reservoir. Constant pressure was maintained in the hydrogen reservoir by means of a regulated vacuum exhaust port. The liquified hydrogen was supplied to the nozzle through a port in the reservoir bottom.

The nozzle assembly consisted of a 1/4-inch-outside-diameter glass tube which had been drawn into a taper. The nozzle tip was lapped to the desired orifice size and flatness. A glass-to-metal-to-ceramic seal was formed between

FIGURE 17 — HEAT EXCHANGER ASSEMBLY

the nozzle wall and the piezoelectric transducer used for liquid jet excitation. This seal extends the entire length of the transducer and eliminates the need for organic binders.

The nozzle and heat exchanger assembly was supported from below by a 1/2-inch Teflon flange which was mounted on four 1/2-inch-diameter ceramic rods. These rods were suspended from a 1/2-inch stainless steel plate which served

as a vacuum seal to the pyrex chamber wall. It also served as a port for refrigerant, exhaust and supply lines, and electrical connections. This construction allowed the entire assembly to be top loaded so as to facilitate ease of maintenance and system modification.

Pressure in the system was controlled by vacuum regulators manufactured by Lake Shore Cryotronics. These regulators provided ± 0.1 torr controllability from ten to 740 torr and were vastly superior to the previous regulators. These new regulators were mounted in modular, front-loading panels which were interchangeable. With the system in that configuration, production of a liquid argon jet was accomplished using liquid nitrogen as refrigerant. The system cool down time was less than 60 seconds and operation remained stable over all operational periods attempted. Unfortunately, the glass heat exchanger coil failed just prior to an attempt to operate the unit using hydrogen and liquid helium. A manufacturing defect, aggravated by repeated thermal cycling, was blamed for the failure.

A second glass heat exchanger was fabricated. Operation with argon and LN_2 was duplicated immediately. Operation with H_2 using LHe as a refrigerant was initiated, resulting in stable H_2 liquification and delivery to the nozzle assembly. However, convective heating of the nozzle assembly resulted in an excessive thermal load in this region. Liquid H_2 entering the nozzle was vaporized and blocked the passage of fluid through the nozzle.

To minimize the convective heat transfer, a new supporting base was fabricated which incorporated active cooling by circulating the cold gaseous He exhaust from the liquid He reservoir through it. Under these conditions, it was possible to produce two-phase flow at high velocity through the nozzle. Although this was an improvement, a 100-percent liquid stream was required.

A third attempt to produce an acceptable liquid droplet stream was initiated by encasing the nozzle in a separate chamber and operating the six-inch-

diameter encasement chamber at high vacuum to provide thermal insulation. This experiment was not carried out to its completion due to termination of the task. A considerable amount of MDAC and DOE funding had been expended on this task and, although progress was being made, it was felt that the Task 2 Optical Characterization Task was showing more promise for application to immediate national laboratory needs. Therefore, the contract office directed that the work on Task 1 be terminated and the remaining funds be allocated to Task 2.

As a result of this redirection, the actual cryogenic coating experiments were not conducted. Detail design drawings of the coater hardware were completed and are on hand. A few elements of hardware were fabricated. The design studies which were conducted indicate that the coating concept is feasible thermodynamically. A reliable stable pellet generator design has been developed though not finally demonstrated. However, the program objective of demonstrating cryogenic coating concepts experimentally was not achieved.

4.0 OPTICAL CHARACTERIZATION

The three basic pellet characterization techniques which were developed and evaluated in this program are:

- (1) Imagery via incoherent light using photographic film and a solid-state video camera (photomicrography)
- (2) Coarse diffraction pattern analysis (CDPA)
- (3) Airy disk measurements

The three principal pellet descriptors are:

- (1) Pellet radius (r_{id} = inside radius, r_{od} = outside radius)
- (2) Pellet shape (sphericity, solid, or hollow)
- (3) Pellet aspect ratio ($AR = r_{od} / [r_{od} - r_{id}]$)

To a lesser extent, such characteristics as mass, surface roughness, number density, and speed of moving pellets have been of interest. Table 2 shows the estimated ranges for the pellet descriptors and the expected tolerance desired. Range and tolerance requirements have been adjusted to correspond to information acquired since project initiation. One of the goals of this program has been to determine how well each of the optical characterization techniques meets the requirements, as stated in Table 2.

The photomicrography and CDPA techniques included in this program are state-of-the-art computer-compatible approaches. This was felt to be important since automatic (i.e., nonphotographic) characterization techniques are essential for commercialized pellet production of the scope needed for an experimental power reactor (EPR) or a commercial power reactor.

Following contract go-ahead, two optical characterization systems were set up and demonstrated. These systems have been available for immediate application to a variety of fuel pellet characterization experiments. The two systems are introduced below:

A photomicrography system capable of producing conventional photographs of microspheres on film was set up and extended to include the recording of images via a solid-state detector array. An RCA SID 52501 solid-state camera was used to record the pellet image and provide gray scale encoding for input to an LSI-11 on-line microcomputer. Image processing algorithms were developed in FORTRAN to accurately extract pellet dimensional parameters. The objective of this task was to demonstrate pellet diameter and sphericity measurements by a technique amenable to computerized automation. The capability was also demonstrated to optically characterize moving cryo-pellets produced by the pellet generator of Task 1. This demonstration required the design and fabrication of additional timing and control circuitry for the pellet generator system and interface circuitry for computer control.

A second characterization system was developed to demonstrate both the CDPA and Airy disk approaches. Coherent light was used to generate Fraunhofer diffraction patterns in the far field which were recorded by photographic film, the solid-state camera, or a custom CDPA ring/wedge detector. The CDPA system was evaluated for future application in a commercialized pellet production facility. High-speed CDPA was studied for use in characterizing large numbers of pellets within a short time, concentrating on the following tasks:

- (1) Design of the CDPA optical system
- (2) Determination of the tolerances in the CDPA approach for pellet radius, shape, and aspect ratio measurement
- (3) Determination of maximum data rates which a reasonably-sized computer could handle in this application

In order to facilitate the completion of these tasks, a pattern recognition computer program was procured to aid in the analysis of data acquired by the CDPA detector array. In addition, the existing Fraunhofer diffraction computer codes and Mie scattering codes to calculate the fringe patterns from

transparent hollow spheres were modified. Both Mie theory and ray-trace approaches were used in this program.

4.1 COMPUTER-AIDED PHOTOMICROGRAPHY - Photomicrography represents the simplest, most straightforward approach to pellet characterization. It was successfully employed for both solid and hollow cryopellet studies in the University of Illinois cryopellet program. Excellent results were obtained using only conventional optical microscopes (30X magnification) and 35-mm single-lens reflex cameras. To "freeze" the fast-moving pellets, simple capacitor-driven spark light sources (pulse of 0.5 microsec) were used. At MDC, photomicrography was primarily employed to record the pellet images for documentation purposes. Computer-aided image processing was used to extract pellet diameter, shape, and aspect ratio data for comparison purposes. Computer-aided photomicrography was also used to view and to diagnose cryopellets produced by the cryopellet generator task.

The major development activity in photomicrography was to study the use of a solid-state silicon photodetector matrix (solid-state camera) for incoherent light imaging. Devices such as the RCA SID 52501 silicon imaging device (512x320 elements) are inherently computer compatible, and can form the basic optical component of an automated pellet characterization system. The solid-state camera was interfaced to the MINC-11 microcomputer through a Quantex DS-12F digital image memory (frame grabber). The frame grabber is a storage buffer for the solid-state camera so that frames may be frozen, thus freeing the computer from the difficult task of storing real time video data. The frame grabber memory also provides a convenient place for manipulation of the video data by the computer.

Image enhancement and parameter extraction algorithms were written in FORTRAN-IV to extract pellet diameter and sphericity. Enhancements included

contrast stretching, edge detection, smoothing, and binary thresholding. The simplest parameter extraction algorithm finds the centroid of the bit pattern representing the pellet shadow. Once the coordinates of the pellet centroid are determined, the distances along a set of radial vectors from the center to the edge can be calculated. This amounts to calculating the radius of the pellet in a number of directions to determine the sphericity. This procedure computes the average pellet radius and the deviation of the pellet shape from the desired spherical form.

The basic resolution to which pellet diameter can be measured depends upon the number of resolution elements along the smallest dimension of the detector array (320 elements) or the frame grabber (256 elements), whichever is smaller. Thus, if the microscope magnification is adjusted so that the pellet image nearly fills the detector array and frame grabber without spilling over, one can expect one part in 256 ($\approx 0.4\%$) resolution in the pellet diameter measurement.

Aspect ratio measurements of hollow pellets using the solid-state camera are not as straightforward as the pellet radius and shape measurements. The image enhancement algorithms must be capable of identifying the pattern that is characteristic of the pellet shell. During this program, the image analysis techniques did not progress to the stage necessary for aspect ratio measurements.

The following paragraphs summarize the progress made on the photomicrography phase of this program.

4.1.1 Optical System Development - The first activity under photomicrography involved making photographs of stalk and slide-mounted glass microspheres and microballons. A prototype photomicrography setup was assembled in a darkroom to gain familiarity with the equipment prior to integration with

the cryopellet generator. Parts were fabricated to adapt the available cameras to the microscopes. The necessary techniques were also developed to mount glass microballoons on glass stalks. This enabled repeated measurements on selected microballoons by different characterization techniques as the project progressed. Several photographs of stalk mounted glass microballoons and microspheres were taken with the bench-top prototype photomicrography system. This system was later interfaced to the solid-state television camera and video frame grabber.

A series of photomicrographs of glass beads and microballoons with a corresponding series of Fourier transform diffraction pattern photos was produced. These photomicrographs were made on Polaroid film, using the bench-top microscope system. By comparing the photographs of the pellets with the photos of the diffraction patterns, it was thought that a better understanding of the patterns produced by the various pellet forms would emerge. Study of these photographs does reveal some interesting features of pellet diffraction patterns. Figure 18 is a photograph of the bench-top photomicrography system used to produce the photos in Figures 19 through 30. A variety of sizes of pellets are presented, as well as some samples of various types of defective pellets.

Final assembly of the cryopellet photomicrography system began upon receipt of the necessary microscope accessories from Ealing Corporation. Provision was made in the design of the cryopellet generator for inclusion of these optics. The key component in this system is the Tetravar unit, which is essentially a two-position switchable beamsplitter allowing selection of an

FIGURE 18 — BENCH-TOP PHOTOMICROGRAPH SYSTEM

GP79-9068-15

184 MICRON DIAMETER SOLID GLASS MICROBEAD

FIGURE 19 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-11

OUT OF ROUND SOLID BEAD WITH BUMP

FIGURE 20 – FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-12

DOUBLET SOLID GLASS MICROBEAD

FIGURE 21 – FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-13

**105 MICRON DIAMETER SOLID GLASS MICROBEAD WITH
ATTACHED 17 MICRON SATELLITE**

FIGURE 22 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-14

MICROBEAD WITH OFF-CENTER BUBBLE

FIGURE 23 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-16

LARGE CLUSTER OF SOLID GLASS MICROBEADS

FIGURE 24 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-17

SOLID GLASS BEAD WITH SURFACE DEFECT

FIGURE 25 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-19

ELLIPSOIDAL SOLID GLASS BEAD WITH SATELLITE

FIGURE 26 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-22

IRREGULAR GLASS CHIP

FIGURE 27 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-24

47 MICRON DIAMETER HOLLOW GLASS MICROBALLOON

FIGURE 28 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-23

MICROBALLOON WITH IRREGULAR SURFACE DEFECT

FIGURE 29 — FOURIER TRANSFORM DIFFRACTION PATTERN

GP79-9068-21

TWO GLASS MICROBALLOONS TOUCHING

FIGURE 30 — FOURIER TRANSFORM DIFFRACTION PATTERN

optical path to either a Polaroid camera or the solid-state video camera. Live viewing through an eyepiece is possible at all times. With the receipt of the Tetravar unit from Ealing, the video photomicrography system, shown schematically in Figure 31, was installed on the pellet generator. This initial cryopellet photomicrography system was positioned to view particles at the generator nozzle exit, as shown in Figures 32 and 33. Similar systems could be placed at other locations in the cryopellet system to monitor pellet trajectory, coating, or other parameters. Polaroid photos of the pellet stream were made, as well as digital storage of closed-circuit television images in the frame grabber. A photo taken from the screen of the video monitor is shown in Figure 13.

4.1.2 Software Development - A major thrust of this effort was to develop computer programs for the manipulation of the digitized video data. Programs were written to record video data, perform contrast stretching, edge contrast enhancement, and line-by-line examination of individual frames. Later develop-

FIGURE 31 — CRYOPELLET PHOTOMICROGRAPHY SYSTEM

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FIGURE 32 — PHOTOMICROGRAPHY SYSTEM A2 USED WITH CRYOPELLET GENERATOR

FIGURE 33 — PHOTOMICROGRAPHY SYSTEM-MICROSCOPE, CRYOPELLET GENERATOR, AND STROBE LIGHT

ment included programs to perform calibration of the digitized images, and to find and characterize circular (spherical) objects within the field of view. A block diagram of the data system is shown in Figure 34. Figure 35 is a photograph of the system as configured for video image analysis.

Progress was made on improving some of the previously developed programs on the MINC. A new edge detection program based on the technique of Sobel⁴ was written. It performed better than any of the techniques used up to this point.

Figure 36 contains three photographs of a solid microbead as stored by the frame grabber. Photo A is the as-recorded image direct from the solid-state video camera. Photo B is the same microbead after Sobel edge enhancement. Note that all edge regions became black, while all other areas were

fig 34

fig 35

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FIGURE 34 — PHOTOMICROGRAPHY DATA COLLECTION/ANALYSIS SYSTEM

FIGURE 35 — VIDEO IMAGE ANALYSIS SYSTEM

FEATURE EXTRACTION BY SOBEL EDGE ENHANCEMENT

ORIGINAL IMAGE

EDGE ENHANCED

THRESHOLD EDGE MAP

FIGURE 36 — IMAGE ANALYSIS

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suppressed to a uniform gray background. Photo C is an "edge map" made from Photo B. All white regions above a certain threshold remained white, while all regions below the threshold were made black. This photo represents the data that would be used as input to a parameter extraction algorithm.

During the course of this program, several image analysis techniques were studied which appeared to have potential application to pellet characterization. One of these analysis techniques is template matching. In this technique, a replica of the object of interest (e.g., a circle) is compared to all unknown objects in the image field. The template is sequentially scanned over the image field and the common region between the template and the image field is compared for similarity. The algorithm computes a difference measure between the template and the image field at all points, and then detects an object wherever the difference is smaller than a preset threshold. A program was written to perform this operation for a simple geometric object, such as a square or a circle. In order to use the technique for parameter extraction, several templates would have to be created to span a range of pellet sizes.

Also, the simple threshold detection criterion would have to be expanded to detect pellets with defects and to determine circularity (sphericity). This technique was not developed to the point of performing pellet parameter extraction due to its complexity and the large amount of computer time needed to exercise the algorithm.

Effort was then redirected toward furthering the development of the image analysis software used by the photomicrography system. The then existing programs written for image enhancement operated on disk files containing previously stored digital image data. This method was suitable for early software development efforts, but was slow and required the major portion of the floppy disk to be devoted to data file storage. Therefore, the programs were modified to perform the image enhancement within the digital image memory (frame grabber). This speeded the analysis process considerably, and allowed the result of an operation to be seen developing "live" on the video monitor.

Once the image enhancement programs had been rewritten in this manner, image analysis programs were written to extract pellet parameters from the enhanced image. One routine located the centroid of the circular image, and did horizontal and vertical searches for the image edges. It computed a first order estimate of the pellet radius and noncircularity based on the orthogonal 1-D scans. If the first order estimate of circularity was within a preset limit (typically one percent), a second routine did a 2-D scan about one of the pellet diameters to locate small defects and large-scale noncircular regions on the surface. This analysis was done on a binary edge map produced by the Sobel algorithm described above.

Use of this technique to analyze computer-generated ellipses has demonstrated the ability to measure pellet diameter to within one percent and to detect eccentricities of less than 0.5 percent. The resolution can, of course,

be improved by using a frame grabber with more memory, e.g., 512x512 pixels rather than 256x256 pixels. The major limitation of this technique is the inability to detect features which do not cross the edge of the pellet as seen by the video camera. This difficulty can be partially overcome by viewing the pellet from multiple angles and by making the image enhancement sensitive to surface features on the pellet. Until the present time, however, the technique has only been used to determine pellet diameter and overall sphericity.

The various programs which had been written to perform the separate steps in the analysis process were then combined into a single program capable of performing any or all of the steps in a programmable sequence. This program, called PELLET, operates directly on digitally-stored images in the Quantex frame grabber memory. In addition to the image processing function, PELLET is also able to do real time acquisition of video pellet images from the cryo-pellet generator. The program, operating on the MINC-11 microcomputer, is synchronized through the external clock and trigger functions of the MINC clock module. An external signal generator and synch circuit provides the excitation signal to the nozzle transducer and a synchronized trigger to the computer and a strobe lamp. A frequency divider and phase shift circuit allows the pellet images to be captured at a precisely known position within the camera's field of view at any submultiple of the basic transducer frequency.

The functions which can be performed by the PELLET program are listed below:

- o Real time image acquisition
- o Image storage on floppy disk
- o Contrast stretching
- o Digital smoothing
- o Sobel edge enhancement
- o Threshold binary image production
- o Calculation of pellet diameter and sphericity

A second program, called CALIBR, performs the calibration function. A standard graticule slide (traceable to National Bureau of Standards) is placed at the object plane of the photomicrography system. After the image is stored, the distances between known points on the graticule are measured. These measurements are converted into calibration factors in terms of microns per pixel in both horizontal and vertical directions.

Listings of both PELLET and CALIBR are reproduced in Appendix A.

4.2 COARSE DIFFRACTION PATTERN ANALYSIS - It is apparent that appreciable computation and computer storage capability is required to measure pellet parameters via incoherent light imagery. While this is not a serious problem in the kind of pellet studies undertaken in this program, it is not tolerable for situations in which tens of pellets per second must be characterized. Anticipating such requirements in future pellet production, high-speed CDPA for pellet characterization has been studied in this program.

The CDPA system exploits the ability of simple lenses to project the Fraunhofer diffraction pattern of a coherently illuminated object at a finite distance.⁵ For an aperture or object located at the front focal plane of a lens, the image formed at the back focal plane is the exact Fourier transform of the object geometry. A circular aperture or a spherical object produces a pattern consisting of a bright central spot (the Airy disk) surrounded by a series of concentric bright and dark rings. The separation of these rings varies as $1/a$, where a equals pellet radius, according to Airy's formula.⁶ For a large object, the ring spacing is quite small, and for smaller objects, the ring spacing increases. The result of this Fourier transform operation is an optical processing technique which is very sensitive to small differences in diameter of small spherical objects. Furthermore, defects on the surface

or within the volume of the object produce easily recognizable distortions of the ideal circular diffraction pattern. Due to the properties of the Fourier transform, the pattern is also insensitive to linear motion of the object, thus making the technique useful for characterization of moving pellets.

CDPA uses a specially designed silicon detector array on which the complete pellet Fraunhofer diffraction pattern is projected. The CDPA detector array, supplied by Recognition Systems Inc (RSI) of Van Nuys, California, consists of 32 wedge-shaped elements for detecting patterns made by edge features and 32 annular ring elements for measuring the distribution of energy with spatial frequency. A distinct advantage of CDPA over imagery with the solid-state camera is the immense reduction in bandwidth. Instead of 65,536 pixel samples to store and manipulate, CDPA requires only 64 samples of the diffraction pattern power distribution on which a pellet measurement is based. Approximately 100 microseconds are required to digitize the 64 samples using special sample and hold circuits in the RSI-supplied high-speed diffraction pattern sampler (HSDPS). The digitized signals are then transmitted over a high-speed parallel interface to either the MINC-11 microcomputer or the PDP-11/40 experimental data gathering and reduction (EDGAR) minicomputer.

A breadboard optical system based upon this technique has been used to demonstrate the basic feasibility of this approach. Figure 37 is a block diagram of the CDPA optical system. The beam from a three-mW helium-neon laser is spatially filtered to reduce speckle pattern effects and collimated into a five-mm-diameter beam. For the purpose of demonstration and experimentation, a mirror arrangement bends the collimated beam so that a glass bead resting on a microscope slide may be illuminated by a vertical beam. This folding mirror system is omitted from the figure for clarity. Another mirror, between the object and the Fourier transform lens, folds the beam back into the original line of sight through the lens.

The spatial filter and Fourier transform lenses are part of a packaged Fourier optical system from Space Optics Research Laboratories (SORL). The spatial filter is composed of an X40 microscope objective focussed onto a ten-um pinhole. The lenses are $f/5$, 7.6-cm-diameter with 32 lines/mm resolution and $\lambda/8$ wavefront accuracy when used at $0.6328 \mu\text{m}$.

The detector placed at the Fourier transform plane is the special-purpose RSI silicon detector array made up of 32 radial wedge elements and 32 concentric semicircular ring elements. The wedge-shaped elements are used for detecting edges and their orientation; the annular ring elements measure the distribution of diffracted energy with spatial frequency. A diagram of the detector geometry is shown in Figure 38.

The 64 signals from the detector array are scanned, amplified, and digitized by the RSI HSDPS, as shown in Figure 39. The digitized values are

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FIGURE 38 - COARSE DIFFRACTION PATTERN DETECTOR

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FIGURE 39 - CDPA DATA COLLECTION/ANALYSIS SYSTEM

transmitted first to the MINC-11 microcomputer for preprocessing and screening. The data is then retransmitted to EDGAR for full-scale pattern recognition processing. The computer processing of diffraction patterns is done by statistical pattern recognition algorithms developed by RSI. One program, called MISTIC, performs a sorting of objects into classes. These classes are determined by a learning process which relies upon the calculation of a statistic known as mutual information. A statistically large number of known samples of each class is required to compute the mutual information statistics for a sample set. Using MISTIC, a set of features can be determined which maximize the mutual information of the sample set. The samples can then be sorted by a binary ranking algorithm which allows any new object not in the original sample set (an unknown) to be classified according to the ranking of the known samples.⁷ A second program, called STAR, computes regression coefficients for any independent parameter as a function of specified dependent parameters. Types of regression available are linear, multiple linear, and polynomial. This program can be used to quantify a set of parameters (e.g., diameter, sphericity, or surface roughness) based upon the observable features of a diffraction pattern. The total software package from RSI includes MISTIC and STAR as well as routines for data manipulation and editing. The entire package is referred to as the automated diffraction pattern acquisition and classification system (ADPACS).

The following summarizes the progress made on the CDPA phase of this program.

4.2.1 Optical System Development - The same optical system was used for the CDPA system as for the Airy disk development. The major difference between

the two is the location of the image plane: for the CDPA system, the pattern's Fourier transform image is used. Work on both Airy disk and CDPA optical systems progressed at the same rate. Enough optical components were available to allow setup of both systems at the same time.

Breadboarding of the CDPA optical system began with the delivery of the Fourier transform optics from SORL. Preliminary work then began on gaining familiarity with the technique. Optical alignment of the components was found to be particularly sensitive, as was the position of the detector or camera used to record the pattern. While the optical system was still under development, preliminary results with objects other than spheres were promising. Spatial filtering of the zero-order peak was sometimes necessary to record the diffraction pattern. Three recording methods were used with the optical system: the high-speed diffraction sampler with ring-wedge detector, the solid-state TV camera, and the Graphlex 4x5 view camera with Polaroid back.

Development of the breadboard Fourier transform optical system proceeded into July 1979 when the first photographs of diffraction patterns from pinhole apertures and solid glass microspheres were obtained. The Polaroid back on the Graphlex camera was used to record the patterns. The photos of the pinhole diffraction patterns, shown in Figure 40, were presented to the DOE review.

The photos showed dramatic evidence of the striking difference between patterns generated by pinholes of varying diameter. Photos of the pattern produced by multiple glass spheres on a glass slide were also made at this time. These photos demonstrated that the major obstacle to this technique was the low contrast pattern produced by a transparent sphere. This problem amounts to one of improving the signal-to-noise ratio of the optical and recording systems.

Good progress was made subsequently toward the goal of photographing and detecting diffraction patterns from single solid microspheres. By mid-August

1979, the pattern from a single 200-micron-diameter solid glass microbead had been photographed (Figure 41). The most urgent problem at that time was mounting the pellets for study. No adhesives or mechanical stalks could be used to hold the pellets. All work done up to that point had been on pellets held electrostatically to vertical glass slides. This technique proved to be tedious and time consuming. Typically, one out of five pellets remained on the slide long enough to be measured and photographed. A horizontal slide holder was developed, but the extra mirrors required caused more scattered light to enter the collection optics. (This was a complication which would not be necessary for characterizing moving cryospheres or other pellets in a production environment.) The horizontal pellet slide holder was installed in the breadboard optical system. It allowed glass beads and microballoons to be held in the laser beam for an indefinite period of time. As a result of that modification of the optical system, measurements were made on photographs of diffraction patterns produced by solid glass microspheres. The major ring structure observed agreed exactly with that predicted by Airy theory for circular apertures. That was a significant result, which confirmed the soundness of the optical system being used.

Photographs of microbead diffraction patterns are shown in Figures 42 through 47. Figures 42 and 43 show diffraction patterns of the same 270-micron-diameter glass bead with different exposure times used to record the patterns. Figures 44 through 47 show diffraction patterns of glass beads which vary in the degree of sphericity. Figure 44 is of a good spherical 169-micron-diameter solid glass bead. Note the clear concentric rings around the central maximum. The diameter of the sphere may be calculated from the radius of any of the bright or dark rings by Airy's formula. Figure 45 is of a solid glass bead with a defect. The diameter of the main bead is 179 microns, with a protrusion

22 μ DIA APERTURE

44 μ DIA APERTURE

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FIGURE 40 — FRAUNHDFER DIFFRACTION PATTERNS BY FOURIER TRANSFORM OPTICS

FIGURE 41 — DIFFRACTION PATTERN FROM 200-MICRON MICROSPHERE

FIGURE 42 — DIFFRACTION PATTERN OF A 270-MICRON-DIAMETER GLASS BEAD,
1-SECOND EXPOSURE

FIGURE 43 — DIFFRACTION PATTERN OF A 270-MICRON-DIAMETER GLASS BEAD,
3-SECOND EXPOSURE

**FIGURE 44 — DIFFRACTION PATTERN OF A GOOD SPHERICAL
169-MICRON-DIAMETER SOLID GLASS BEAD**

**FIGURE 45 — DIFFRACTION PATTERN OF A 179-MICRON-DIAMETER
GLASS BEAD WITH A 15-MICRON BUMP DEFECT**

**FIGURE 46 — DIFFRACTION PATTERN OF A 160-MICRON-DIAMETER
GLASS BEAD WITH A 60-MICRON BUMP DEFECT**

**FIGURE 47 — DIFFRACTION PATTERN OF A 210 X 120-MICRON
RECTANGULAR BEAD**

of about 15 microns on one end. This protrusion is apparent from the noncircularity of the rings in the pattern and the bright linear features which form a fuzzy "X" across the pattern. The linear features are oriented orthogonally to corresponding flat spots on the bead. Figure 46 is another defective bead. In this case, the bead is actually a doublet formed by a 162-micron bead with a 60-micron hemisphere on one side. The degradation in the structure of the rings is marked and more linear features are observable. The linear features in this case are caused by the corners where the two beads are jointed. Figure 47 is of a bead which is more like a rectangular box with rounded corners than a sphere. The bright lines in the pattern are caused by the flat sides. The ring spacing in any dimension is indicative of the dimension of the pellet along that radial direction. The relation between ring spacing (spatial frequency) and pellet dimension is inverse, so the area with close spacing indicate the long dimension of the pellet. There is no simple formulation to determine the dimensions of an arbitrary pellet such as this. However, the shape of the pellet could be approximated by a two-dimensional Fourier transform of this pattern.

Referring again to Figures 19 through 30, several kinds of diffraction patterns are illustrated, which result from the various sizes of glass beads and microballoons, as well as deformed patterns from defective pellets. These diffraction patterns were evaluated in terms of information content, as recorded by the HSDPS and ring-wedge detector. This evaluation aided in the optimization of the HSDPS electronics and in the use of the pattern recognition software. Figure 48 is a photograph of the CDPA optics used to produce all the diffraction patterns presented here.

The four five-axis lens mounts from Newport Research Corporation arrived at the end of November 1979. This completed the procurement of optical parts

FIGURE 48 – COARSE DIFFRACTION PATTERN ANALYZER OPTICAL SYSTEM

for the CDPA system. The lens holders in two of the mounts were machined to accept the Fourier transform lenses; the post mounts were replaced when this was done. These mounts were used to support the Fourier transform lens and the RSI ring-wedge detector. The stability of the optical system was improved considerably. All previously recorded diffraction pattern data were duplicated within a few days after completing the modification. Photos of the new optical system are shown in Figures 49 and 50.

4.2.2 Moving Pellet Considerations - During the course of this program some questions were raised concerning speed of data acquisition and smearing of the diffraction patterns caused by moving pellets. After careful evaluation of the questions, the following conclusions were reached.

Speed of data acquisition should not be a limitation on the system. A concept under consideration is to integrate the signal from the ring-wedge detector over the entire time which the pellet spends traversing the laser

FIGURE 49 — NEW MOUNTING CONFIGURATION FOR FOURIER TRANSFORM LENS AND RING-WEDGE DETECTOR

FIGURE 50 — MODIFIED BREADBOARD OPTICAL SYSTEM FOR COARSE DIFFRACTION PATTERN ANALYSIS

beam. The diffraction pattern remains stationary on the detector regardless of the position of the pellet. This is one solution to the low signal-to-noise problem.

A spinning or rapidly moving pellet will not distort the diffraction pattern to any significant degree. First, motion does not affect the spatial frequency of the pattern which is recorded by the rings. This is not an imaging technique, so the "image" is not translated by object motion. Secondly, rotation of the pellet can only affect the orientation of a feature (defect) as seen by the wedge elements. A 100-micron pellet traversing a one-mm-diameter beam at one meter/second traverses the beam in 1.1 milliseconds. Each wedge element subtends an angle of 5.6 degrees. Therefore, to blur the diffraction pattern over two wedges, the pellet would have to be rotating at over 13.0 revolutions/second (780 rpm). It seems doubtful that moving pellets will have this magnitude of rotational energy. At higher translational velocities, e.g., 20m/s, which is typical for a cryopellet generator, spin becomes even less important due to the shorter beam traversal time.

4.2.3 Data System and Software Development - A link between the HSDPS and EDGAR was planned, making real time acquisition of diffraction pattern data possible. A link between the HSDPS and the MINC-11 microcomputer was also developed. The establishment of the data link between the HSDPS and EDGAR was delayed, however, when the DR11-B parallel interface unit purchased for this was found to be defective and repair by Digital Equipment Corporation (DEC) field service was required. In the interim, the link between the HSDPS and the MINC-11 microcomputer was completed. Data were collected by the MINC through the digital input module, displayed on the MINC's VT105 graphic terminal and then transmitted to EDGAR on a serial data line. The pattern recognition software on EDGAR then processed the diffraction pattern data.

During the first two months of the program, the installation of the ADPACS software had progressed to the point where all the relevant programs had been task-built and demonstrated. A software specialist from RSI delivered the software package and adapted the ADPACS pattern recognition software to our EDGAR system. A one-week period in March 1979 was spent editing the software for our configuration. The task building was successfully completed in early April 1979. Due to the multiuser nature of EDGAR, it was necessary to split ADPACS into several separate computer programs in order to fit it into the memory. The slow task builder (STB) was installed into EDGAR's RXS-11M system to enable RSI to build the ADPACS tasks (MISTIC, STAR, etc.). These tasks overflow the symbol table of the normal task builder (TKB).

A three-day seminar included with the ADPACS package by RSI was held the week of 18 June 1979. During this time, personnel involved in Task 2 were tutored in the use of the pattern recognition programs and presented with a series of lectures on the theory of pattern recognition as applied by the software.

A limited amount of software development was done on the MINC in order to facilitate the recording and evaluation of diffraction pattern data from the HSDPS. For example, a program was written which plots a histogram of HSDPS ring element data in real time. This program was then expanded to allow comparison of different data sets as well as background subtraction, scaling, and the calculation of sample to reference ratios. The data acquisition program was also enhanced to include signal averaging.

The pattern recognition software was first demonstrated on diffraction patterns from 35-mm slides of geometric patterns (squares, circles, triangles, etc.). The MISTIC pattern classification algorithm demonstrated the ability to sort the patterns into correct classes with no incorrect decisions. The

experience gained through this exercise was extended to the classification of microspheres.

Files containing 20 different microbead diffraction patterns were recorded on floppy disk by the MINC, and attempts were made to perform pattern recognition on these first data files. The results were inconclusive, thus work was begun to simplify the pattern recognition programs to make the analysis faster and more straightforward. The algorithms themselves were not complicated, but the structure of the program was so detailed and complex as to make the data analysis cumbersome. An attempt was made to streamline the programs to make them more applicable to the requirements. This effort to simplify the pattern recognition software continued into November 1979, but did not meet with success. The programs (ADPACS, MISTIC, and STAR) contained an extensive data structure comprised of numerous FORTRAN common block arrays. These arrays were not set up in accepted programming practice, and the usage and purpose of many array elements are quite obscure. As a result, attempts to simplify the programs were limited in effect. Some apparently innocuous changes in coding caused inexplicable malfunctions in execution of the programs. These problems completely frustrated the effort to simplify the pattern recognition programs.

A low-priority backup effort began to extract the algorithms from the pattern recognition programs and rewrite them into other programs capable of running on either EDGAR or the MINC. This effort would have had several benefits if carried to completion. First, a more complete understanding of the algorithms would have been obtained by rewriting them rather than by merely using them. Secondly, a version of the algorithms more closely suited to the specific pattern recognition task would be available. This would reduce the large amount of generality built into the programs for fixed procedures and structures appropriate to small particle characterization. Finally, there

would be a head start on the small microcomputer-based pattern recognition program which necessarily would be part of a production characterization system. As mentioned above, this was a low-priority item which was considered as a long-range alternative to using the programs as-delivered.

To date, the CDPA system has demonstrated the ability to sort a distribution of glass microbeads into five 20- μ m wide size range classes from 100 to 200 μ m with no misclassifications using the MISTIC pattern recognition program. Rejection of pellets with obvious defects has also been demonstrated. The pattern recognition software operates interactively, and is not capable of processing the diffraction patterns of moving pellets in real time. However, the CDPA breadboard as it exists at the conclusion of this program is well suited to the investigation of pellet diffraction patterns and to the refinement of the pattern recognition algorithms.

4.3 AIRY DISK OPTICAL SYSTEM - With coherent background illumination, a Fraunhofer hologram or diffraction pattern of a pellet is observed in the far-field region. There is a bright central spot centered on the axis of the incident light. The diameter of this bright central spot, or Airy disk, is given by:

$$D(A) = \frac{1.22 Z \lambda}{a}$$

where Z is the distance between the pellet and the plane of observation, λ is the wavelength of incident light, and a is the pellet radius.⁶ This equation essentially defines the diameter of the Airy disk in the diffraction pattern and relates it to pellet size. It was intended to carry out experiments to study the feasibility of Airy disk measurements on diffraction patterns much as the CDPA subtask was carried out. However, after some experience with the CDPA optics was gained, it was determined that the Airy disk approach was not sufficiently different from CDPA to warrant a separate experimental approach.

In fact, it was apparent that the Airy disk technique was a subset of the CDPA technique. Subsequent effort under this heading was directed toward the development of computer codes which could be used to predict the diffraction patterns associated with both CDPA and Airy disk methods.

The following describes the progress made toward developing these diffraction pattern modeling codes.

A major goal of optical characterization was to develop analytical models which could predict the diffraction patterns associated with Airy disk measurements and coarse diffraction pattern measurements. To this end, development of a computer program to compute the Fraunhofer diffraction pattern of arbitrary geometry was begun. This program was based upon the fast Fourier transform (FFT) method described by Sziklas and Siegman.⁸ In its early form, the program considered only diffraction of a plane wave by a two-dimensional amplitude and phase object.

In order to extend this analysis to the case of a three-dimensional refracting particle, the spherical wave coordinate transformation of Sziklas and Siegman was studied for possible incorporation into the program.⁹ The disturbance produced by a coated spherical particle can be calculated by a Lorentz-Mie scattering program such as one developed by Brunsting and Mullaney.¹⁰ The angular amplitude and phase distribution calculated by this program can be used as input to the FFT program.

The Lorentz-Mie computer code for calculation of scattering by coated spheres was purchased from A. Brunsting of Coulter Electronics. The program was installed on EDGAR. This program was used as the initial phase in an effort to model diffraction patterns produced by microballoons and other layered spheres. Simulated patterns thus computed could be used as templates by the pattern recognition software.

During July 1979, the Lorentz-Mie computer code, purchased from Brunsting for the calculation of scattering from layered spheres, was received. The subroutines and example programs were immediately typed into EDGAR. Several of the routines were verified to produce the correct results. A test program to compute scattering from a solid sphere was debugged. The program was then extended to reproduce data from layered spheres. This procedure was recommended by Brunsting due to the size and complexity of the individual routines.

During August, all of Brunsting's suggested examples were run, then published results were duplicated. The code was modified to permit calculation of scattering parameters for the relatively large diameter spheres of interest to inertial fusion. This necessitated doing most of the calculation of scattering parameters with logarithms due to the large magnitude of the spherical Bessel functions, e.g., 10^{150} . This modification made it possible to compute scattering parameters for layered spheres up to several hundred microns in diameter. The program modification progressed smoothly, and was completed without difficulty.

After the Brunsting code was complete, work began on the spherical wave coordinate transformation and integration with the FFT program. Unfortunately, this work did not progress as expected and was never completed within this program. However, a great deal of experience has been accumulated on this type of modelling which could be of value as the pellet characterization techniques mature.

Diffraction patterns of circular amplitude and phase objects similar to coated spheres were also calculated by a more simple program based on an existing two-dimensional FFT program developed in-house. The basic assumption used here is called the "localization principle." This assumption treats the

light rays passing through the pellet as if they went straight through without refraction or diffraction at the surfaces of the pellet. This calculation can be used to predict the approximate locations of minima and maxima in the diffraction pattern, but it does not predict the fine structure of the pattern. The full Lorentz-Mie theory must be used to predict both the geometry and the amplitude function of the pattern.

4.4 SUMMARY - Progress was made toward understanding the strengths and weaknesses of the three optical characterization techniques studied under this contract. The computer-aided photomicrography task was used to form a simple pellet screening system for an experimental production-rate pellet generator. The system was demonstrated to measure pellet diameter to within one percent and to detect eccentricities of less than one-half percent. A weakness of the present system is the inability to detect features which do not cross the edge of the pellet as seen by the camera. The difficulty of interpreting features visible within the pellet image is also a disadvantage of computer-aided photomicrography. However, use of multiple optical systems and more sophisticated image analysis computer programs may be able to resolve these difficulties in the future. The hardware and software developed under this program could serve as the basis for a prototype production-rate photomicrographic pellet screening system.

Work done under this contract has also shown that coarse diffraction pattern analysis using Fourier transform optics can be used to perform pellet characterization. The breadboard optical system and pattern recognition programs have shown that CDPA can be used to detect pellets and sort them by size. Rudimentary selection of defective pellets has also been demonstrated. The dramatic differences observed in pellet diffraction patterns due to the presence of defects make CDPA an attractive technique for further development.

More work should be done to determine the sensitivity of CDPA to the localization and quantification of pellet features and defects.

Finally, a foundation for a comprehensive scattering model of a typical layered IF pellet has been laid by this work. The simulation of the diffraction patterns and images produced by even simple inertial fusion pellets is a complex task. However, the modelling programs begun under this contract can serve as a first step toward sophisticated models of the optical properties of pellets necessary for the evaluation of characterization techniques.

5.0 TRANSPORT SYSTEM

5.1 BACKGROUND - The transport system task involved the development of an electrostatic pellet motion control system. A system for the accurate control of pellet motion is essential to the full automation of any mass-produced, automated-fueling system for ICF reactors. Such control in the early production process would allow adjustments of pellet velocity and position during the forming and coating processes to assure the production of well-formed spherical pellets with uniform wall thicknesses and coatings. During the initial characterization phase, automated pellet inspection may require the exercise of selective pellet motion control. The later coating phases may require accurate injection of the pellet into a small orifice of a coating chamber at a specific velocity. Finally, the steps necessary to produce the final coated pellet may require a high degree of trajectory and velocity control, although perhaps using different techniques than those used for the pellet production process.

Various schemes have been proposed for controlling the motion of micro-particles, but the most developed approaches rely upon electrostatic forces. Such systems have been used at the United Technology Research Center successfully to catch and suspend microspheres in plasma mirror systems, and work has been done at the University of Illinois to accelerate and control frozen hydrogen pellets for injection into Tokamaks.

The task objective was to demonstrate the capability to control the motion of dielectric pellets sufficiently to allow selected discrete particles to be steered through space to specified locations with controlled velocity vectoring.

5.2 PELLET TRANSPORT AND CONTROL SYSTEM - Techniques and equipment for pellet motion control during the pellet fabrication and characterization

process will be necessary for high production rates. Electrostatic and pneumatic control systems have been developed sufficiently to produce reasonable confidence that a control system for noncryogenic conductive particles can be demonstrated. However, the charging and control of cryogenic dielectric fuel poses many additional problems. Because the operation of a cryogenic pellet fabrication system which included operation under vacuum conditions was contemplated, the pneumatic approach was ruled out.

Electrostatic control involves three principal factors. First, the particle to be controlled must be charged sufficiently so that the resulting charge-to-mass (q/m) ratio allows the particle to be moved at a useful rate by reasonable voltages. Second, there must be some knowledge of the velocity and position of the particle, and, finally, there must be provisions for establishing the proper electric field vectors at the precise time and location to affect the desired acceleration of the particle.

A number of techniques have been developed for electrostatically controlling the motion of microparticles. Reference 11 describes a system which reliably captures an injected particle in the $100\mu\text{m}$ size range and stably positions the particle in the center of the system with less than $20\mu\text{m}$ jitter. Reference 12 describes a system which uses deflection plate steering of an injected particle on the basis of the observed particle velocity and direction. This technique is capable of controlling the position of the particle to within a few diameters of the desired position. Reference 13 describes the electrostatic control activity at the University of Illinois, which is still under development.

In Reference 14, Charles Hendricks, at the Lawrence Livermore Laboratory, describes a proposed pellet transport system utilizing a circular quadrupole rail system. Electrodes are periodically spaced around the interior of the

track to sense the particle charge and velocity while other stations adjust the charge and velocity to the desired values. The pellets are propelled in a step-wise motion by applying pulses to the electrodes, rather than continuous voltages. The advantage of this approach is that pellets can be positioned (levitated) in one place for a process step such as coating and then moved to the next position at the desired time. The pellet transport is more readily adapted to computerized control, and the pellet position is known precisely at each step. This approach has many attractive features.

Hendricks also points out another advantage of an electrostatic control system which can be realized if spin motion can be applied to the pellets. The concentricity of the inner and outer walls may be determined by spinning the pellet and observing the superposition of the visual image axis on the axis of rotation. The noncoincidence of the two axes is a measure of the non-uniformity of the pellet wall.

The spinning capability may also be desirable during the pure cryopellet freezing process to ensure that a uniform wall thickness is achieved, and during the coating process to ensure that uniform coating is produced.

In References 15 and 16 a pellet trajectory guidance system for the pellet injection system of Baseball II-T is discussed. The system used three detectors and a set of electrostatic lifting plates to determine the mass-to-charge ratio and the trajectory of the pellets. A set of vertical deflection plates and a set of horizontal deflection plates were used to adjust the pellet trajectory. A microcomputer was used to calculate the pellet mass-to-charge ratio, the pellet trajectory, and the voltages for the vertical and horizontal deflection plates. This system was designed to overcome such problems as aerodynamic turbulence, nozzle dispersion, and charge-to-mass fluctuations for a high pellet number flux.

After a careful review of past work, it was decided to build a system modelled after the Baseball II-T system. The system was a more sophisticated and costly system than had been planned. However, a complete set of drawings and schematics was provided by LLL, and the modifications for the pellet generator application were not extensive. A major difference involved the electrical conductivity of the pellets. The Baseball II pellets were doped ammonia, and were conductive enough for inductive charging. Techniques still need to be developed for charging dielectric pellets.

5.3 PARTICLE CHARGING - A limited amount of charge can be applied to liquid droplets by a high-voltage electrode placed within the jet nozzle. The charge per particle is limited by the Rayleigh limit, beyond which the droplet will disintegrate as a result of internal electrostatic forces. After the droplet is frozen into pellet form, additional charge can be added, provided that it can be deposited without excessively heating the pellet.

In the University of Illinois system, shown in Figure 51, the drops were charged by a high potential applied to a very sharp thoriated-tungsten needle. The resulting high fields injected charges into the jet which subsequently broke up into uniformly charged drops. The amount of charge injected into the jet was determined by the current in the tungsten needle circuit which was controlled with a current limiter.

The tungsten needle was electrically insulated from the jet assembly by a glass filament, as shown in Figure 51. A high-voltage electrical connection was made to the tungsten needle by slotting the glass nozzle near the end. A small nickel tube was then placed inside the glass nozzle with a high-voltage line soft-soldered to it. The tungsten needle inside the nozzle was in physical contact with the nickel tube, thereby completing the electrical connection.

FIGURE 51 - DROPLET CHARGING SETUP

The needle was etched in a 0.4-mole solution of sodium hydroxide (NaOH) by a 5-volt, 60-hertz potential. The tip radius was then estimated to be less than 2500 angstroms, through measurements taken with a microscope at a magnification of 315.

The apparatus described in the preceding section successfully produced uniformly charged liquid nitrogen drops in the 200-micron-diameter range. In operation, ten kilovolts obtained from the high-voltage power supply were applied to a current limiter. The current limiter then applied the appropriate potential to the tungsten tip such that a constant amount of charge was continuously injected into the jet. The charge injection current initially started around 5×10^{-9} amperes and was controllable up to its maximum value of 2×10^{-7} amperes. From current measurements, it has been shown that a

maximum charge of 2.64×10^{-12} coulombs per drop can be achieved without destroying the original size of the drops. The Rayleigh limit ($q_{\max} = 4\pi\epsilon_0 TR^{3/2}$) for a drop 188 microns in diameter is 1.38×10^{-11} coulombs per drop, or 5.7×10^{-7} coulombs per gram (C/g). Thus, the drops can be charged to about one fifth of the Rayleigh limit.

An analysis of the maximum q/m which can be maintained on a dielectric sphere indicated that for 100μ -diameter frozen H_2 pellets, the limiting factor appears to be the intermolecular binding energy of the solid phase and leads to a maximum q/m of 2.41×10^{-1} C/kg. This is roughly seven times that which can be achieved with a similar liquid droplet limited by the Rayleigh instability. If it can be experimentally realized, this higher q/m would allow significant simplification of any transport, guidance or detection system. However, the technique required to charge solid, cryogenic spheres after they are frozen is still to be developed. Investigation of the charging of cryogenic hydrogen pellets has revealed four basic techniques. They are contact charging, electron bombardment, proton bombardment, and x-ray irradiation. The latter three techniques have potential applicability, after the gating and freeze process have been completed, to enhance the charge resident on the pellet. In the case of tritium, the charge generated on the pellet by radioactive decay may be all that is needed for control purposes.

5.4. CHARGE MEASUREMENT TECHNIQUES - A number of methods exist by which the charge on a small pellet, or stream of pellets, can be measured. Three alternatives will be discussed here, in order to point out the particular restrictions imposed by the nature of the experiment.

The simplest technique requires that a stream of charged pellets be collected in a metal cup and the resultant current be discharged through a sensitive ammeter. If the number of charged pellets landing in the cup per

second is known, then the average charge per pellet can be computed. It would be given by

$$q = I/N$$

where I is the current measured by the ammeter, in coulombs per second, and N is the number of pellets per second.

A large faraday cup, shown in Figure 52, was built to measure the average charge-to-mass ratio.

FIGURE 52 — ICF FARADAY CUP

The second method of measuring the droplet charge consists of measuring the current before it is injected into the jet with a picoammeter. By knowing the number of drops produced per second, the charge per drop can be obtained. This method could be used in conjunction with the previous method. With the very high charging potential (≈ 10 kilovolts), inaccuracies could be introduced by current leakage along the surface of the high-voltage feed-throughs.

A technique more suited to determining the charge-to-mass ratio of a single drop requires the measurement of the deflection of a charged pellet in a known electric field. A constant electric field will exist between two flat, parallel plates with a potential between them. If a charged pellet with constant velocity passes between the plates and its position is measured two times, separated by a delay of t seconds, it will be deflected from its path by some distance, d . From this data, the charge-to-mass ratio can be computed. It is given by

$$\frac{q}{m} = \frac{2dR}{Vt^2}$$

where q is the pellet charge, m is the pellet mass, R is the plate separation, and V is the potential between the plates, all in MKS units.

5.5 EXPERIMENTAL TRANSPORT AND GUIDANCE SYSTEM - The design of the experimental transport and guidance system (XTRANS), shown in Figure 53, was modelled after the Baseball II-T system. The design called for one pellet per second to be charged and deflected to an orifice which separates the droplet formation chamber (at approximately 50 torr) from the pellet freezing chamber (at 10^{-2} torr). A pulsed corona discharge technique selectively charges the pellets. Charged droplets are deflected to the chamber output orifice by a static electric field. The position of this orifice is vertically and horizontally adjustable.

After the pellet exits the chamber, its trajectory is measured by a series of quadrupole electrodes which it must pass through.

The trajectory monitoring system, shown in Figure 54, is composed of detector assemblies, interface electronics, and an LSI-11 minicomputer. The detector assemblies house the quadrupole electrodes, the detection electronics, temperature monitors, and heaters. The interface electronics locks onto the

FIGURE 53 – EXPERIMENTAL TRANSPORT & GUIDANCE SYSTEM LAYOUT

GP79 9668 1

GP79 9668 2

FIGURE 54 – BLOCK DIAGRAM OF SINGLE CHANNEL OF XTRANS-1 TRACKING SYSTEM

peak signal from each channel and signals the minicomputer when a signal has been acquired. It also measures the time of flight between detectors and performs calibration and examines system health. The LSI-11 minicomputer records all data taken and is used for non-real time data reduction.

The analog peak signal capture circuitry was breadboarded. The breadboard setup revealed a difficulty in the peak detection circuit. This circuit centers around an analog comparator sensitive to five mV differential levels with a TTL compatible output indicator. However, the unit generates noise levels of >100 mV when the digital output changes state. This results in erroneous timing signals being initiated, and failure of the system to capture the peak voltage level. This problem was overcome by isolating all digital logic circuits from the analog data lines.

The physical arrangement of the experimental transport and guidance system is shown in Figure 55. Details about the individual components are given in the following paragraphs.

FIGURE 55 – XTRANS-1 PHYSICAL ARRANGEMENT

5.5.1 Detector Assembly - Figure 56 illustrates the general arrangement of the detector plates, the detector electronics and the temperature control modules. The detector chassis is aluminum and the electrode structure is

FIGURE 56 — XTRANS-1 DETECTOR ASSEMBLY

GP79-906B-46

Macor ceramic. The temperature control element maintains the electronic bays at -10°C . Each detector plate consists of a one-cm-square area of gold plating on the Macor substrate. The electrical impulse produced by capacitive coupling of the charged pellet is coupled from each of the four detector plates to its respective electronic detector and preamplifier circuit board located in the adjacent bay.

The aluminum chassis is shown in Figure 57. Some difficulty was experienced in machining the Macor electrode substrates.

A printed circuit card for the detector electronics is shown in Figure 58. Operation of the units has been checked out satisfactorily.

5.5.2 Digital Control and Timing Electronics - The electrometer amplifiers and the digital timing and control units were assembled and checked out. Figure 59 shows the time base and control logic board. Figure 60 shows the data transfer board.

FIGURE 57 — QUADRIPOLE ELECTRODE CHASSIS

FIGURE 58 — ICF HIGH IMPEDANCE AMPLIFIER ASSEMBLY

FIGURE 59 — INTERFACE ELECTRONICS TIME BASE AND CONTROL LOGIC BOARD

FIGURE 60 — INTERFACE ELECTRONICS DATA TRANSFER BOARD

5.6 TASK TERMINATED - As the total contract program progressed, the DOE scope and emphasis of the program changed from long-term reactor concerns to near-term applications. Since this task was modelled after previous work which was shown to be feasible, the program management office directed that the task be terminated and the remaining funds be directed to Task 2. Consequently, the transport system task was not carried out to its completion.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 PELLET FABRICATION - Cryogenic targets are theoretically the most promising concept for achieving the energy gains needed for an energy-producing inertial confinement fusion reactor. The pellet generators built and operated in this study show great promise as a method of mass-producing low-cost cryogenic targets at the reactor site. The combination of high-energy gains and low-cost is required for inertial confinement to be economically viable.

The cryogenic target is expected to require both pusher/tamper and ablator coatings over the fuel core. The application of these coatings to the frozen fuel pellet was studied. An experimental device was designed to study several cryopellet coating concepts. Fabrication of the coater was delayed when problems with the pellet generator resulted in a complete redesign of the generator. It is felt that the coating concepts are valid and need to be studied and developed into a coating device. Based on this experience, for continuing development it is recommended that a coating of carbon monoxide be applied to argon pellets. This approach uses readily available inexpensive gases and requires only liquid nitrogen as a refrigerant. LN_2 is much easier to handle and less expensive than liquid helium.

The next step would be to extend the coating concept to multiple layers of different gases. This extension would demonstrate the ability to apply both an ablator and a pusher/tamper coating to a cryopellet.

It is recommended that additional effort be spent in developing the hydrogen pellet generator. This generator, while simple in concept, is quite complex in reality. Careful design is required to reduce external heat leaks and to produce good heat transfer in the heat exchanger. Temperature measurement and temperature control are vital to obtaining good repeatable pellets. There are a number of design problems that must be solved so that the position

and direction of the pellet stream can be controlled and still be independent of the droplet chamber. Based on the two cryopellet generators built, it is expected that more refinements of the generator design will be required to fully develop a generator that will reliably produce hydrogen cryopellets of uniform quality.

After the hydrogen cryopellet generator is perfected, the freezing and coating processes should be extended from the argon pellet to the hydrogen pellet. When this program was begun, it was believed that the hydrogen pellet generator was a well-developed apparatus. Now it is known that there is much work to be done to develop a cryogenic pellet for inertial confinement fusion reactors. It is, therefore, recommended that a modest effort be continued to develop the mass production of cryogenic pellets at the same time that other critical aspects of inertial confinement are being developed.

6.2 OPTICAL CHARACTERIZATION - The three optical characterization tasks undertaken as part of this contract have been very productive in terms of gaining an understanding of the problems associated with any inertial fusion pellet characterization technique. None of the techniques studied or demonstrated has progressed to the point of being an obvious choice for a production pellet characterization system. However, progress has been made toward understanding the strengths and weaknesses of each technique. This is in itself an accomplishment which will help in determining the course of future research and development of these techniques.

The computer-aided photomicrography task has shown that a relatively modest computer can be used with appropriate video storage and processing equipment to form a simple pellet screening system for a production rate pellet generator. The MDC in-situ photomicrography system is capable of taking pictures of individual pellets and processing the images to compute diameter

and sphericity in a matter of a few minutes. Nothing inherent in the technique precludes adapting it to processing rates of ten or more pellets per second using larger computers. The limitations in the existing system are:

- (1) A small microcomputer-based processing system using flexible disks as the primary storage medium. A faster microprocessor with hard disks would speed the necessary calculations.
- (2) All image processing software was written in a high-level language, FORTRAN. A high-speed system should have its software coded in the microcomputer's native machine language so as to effect the highest execution speeds. Implementation in read-only memory (firmware) would also make operation more efficient.
- (3) The IEEE-488 interface between the frame grabber and microcomputer. This interface is limited by the controller in the computer; alternate interface designs eliminate the bottleneck and allow the bus to run at its full capability.
- (4) Lack of memory and processing capability in the frame grabber. The Quantex model DS-12F used for this work has only a 256 by 256 pixel memory capacity. This could be expanded to at least 512 x 512 pixels for better resolution. Options are also available which move some of the image processing power from the microcomputer into the frame grabber.

Automated pellet inspection stations similar in principal to our photo-micrography system are foreseen as becoming an integral part of a future pellet production facility. Systems like this could serve as a first-line pellet inspection technique. Obviously defective pellets could be detected easily and gated out of the production stream steps in real time. Statistics on pellet quality could be kept by the computer to determine when production or coating systems were operating out of tolerance or malfunctioning. This technique, while not as exotic or technically as challenging as other state-of-the-art techniques, could rapidly be developed by simple refinements into a pellet inspection tool.

Coarse diffraction pattern analysis, on the other hand, is still in its infancy as a pellet inspection process. Work done under this contract has

shown that pellets can be detected and sorted by CDPA. More work needs to be done in order to determine the sensitivity of the technique to the detection and quantization of pellet features and defects. As with the photomicrography task, the optical system used to perform CDPA experiments has been limited. An improved and more flexible development optical system should be used to perform more sophisticated experiments in CDPA. Experiments should be performed on pellets which have been previously well characterized by other techniques at the national labs. A goal of further experiments would be to determine the correlation between features detectable by CDPA and features and defects observable by other techniques. Experiments should be performed to investigate spatial filtering at the Fourier transform plane, and the effect of using laser wavelengths other than $.6328 \mu\text{m}$ of helium-neon. These experiments would form a logical follow-on to the work done under this contract.

The scattering and diffraction pattern modelling work has shown that simulation of the patterns produced by even relatively simple inertial fusion pellets is not a trivial task. However, the foundation for a comprehensive scattering model for an IF pellet has been laid by this work. More complicated analyses, such as the spherical wavefront transformation of Siegman, should be incorporated into the model. Eventually pellet modelling could be developed into a valuable tool for predicting the ability of different optical techniques to characterize various targets. More emphasis should be placed upon pellet modelling techniques in order to remove pellet characterization from the trial-and-error stage it is in now. In particular, the CDPA technique could benefit from having good models of layered spheres to predict how CDPA could determine aspect ratio and other subtle pellet parameters. Models could be used to predict the response of CDPA to pellets of different geometry and lasers of different wavelength before experiments are performed.

6.3 PELLET TRANSPORTATION - The transporting, manipulation and injection of ICF fuel pellets are critical technologies which may require more development time than either the development of the production system or the development of the characterization system. The work on this program was terminated before any experimental results could be obtained. Hardware was built to charge cryopellets, to measure their charge-to-mass ratio, and to measure their trajectories.

Work should be done to determine the best approach for depositing electrical charge without melting or vaporizing the pellet. Three techniques have been identified for experimentation and evaluation. These are contact charging, electron beam charging, and ion beam charging. The first of these, contact charging, is the technique which was to be used in the initial experiments. This technique is limited by Rayleigh instabilities, beyond which the liquid droplet will disintegrate. The other two techniques offer the possibility of higher charge on the pellet by charging after the pellet is frozen. These techniques also offer the possibility of adding charge to the pellet after its mass is increased by the addition of the tamper/pusher and ablator layers.

The work on charge measurement and pellet trajectory determination should be completed. Much of the hardware has been fabricated and is available.

APPENDIX A

LISTINGS OF IMAGE PROCESSING PROGRAMS

Inclusive pages: 96 - 133

PELLET

```

C PELLET.FOR          Version 01      13-Mar-80      bab
C
C This program is the prototype for the automated ICF pellet
C characterization system. It performs the following functions:
C
C   1) Command the Quantex Frame Grabber to "freeze" the image
C      of a pellet produced by the cryopellet generator.
C
C   2) Process the stored image of the pellet within the
C      Quantex memory.
C
C   3) Report pellet parameters: diameter, sphericity, etc.
C
C The first section of the program includes the code necessary
C to GRAB the pellet image. This is done using the MNCKW real time
C clock module. The configuration is listed below:
C
C   A variable frequency signal generator feeds a high frequency
C   sine wave to the pellet generator ultrasonic transducer and
C   to a digital synchronizing delay circuit. The delay circuit
C   provides TTL pulses (negative logic) to the strobe lamp
C   and to the MNCKW ST2 input. The input to the strobe is delayed
C   approximately 66msec from the input to ST2. This is done to
C   make up for delays in the MINC and in the Quantex. The ST2
C   input is used as a "start-sweep" trigger.
C
C   The vertical drive signal from the solid-state video camera
C   is connected to the ST1 input on the MNCKW and is used as
C   an external clock input. The MINC is programmed to take a
C   1-word, 1-buffer sweep when the clock overflows after ST2
C   is triggered. A completion routine executes after the
C   1-word buffer is filled. The completion routine sends the
C   GRAB command to the Quantex.
C
C -START-----
C
0001      DIMENSION INFO(40),IBUF(1),ICMPLT(1),ISTEP(10)
0002      BYTE BEEP(2),STIM(9)
0003      COMMON INFO
0004      EXTERNAL GRAB
0005      DATA BEEP/"7,0/",STIM/9*0/
C
C Set up the screen format and output the title block.
C
0006      CALL CLEAR(0)
0007      CALL BOLD
0008      CALL REVERS
0009      CALL CURSOR(1,20)
0010      CALL PUTSTR(5,' ICF Pellet Characterization ',0)
0011      CALL CURSOR(2,20)
0012      CALL PUTSTR(5,'      Image Processing      ',0)
0013      CALL NORMAL
0014      CALL CURSOR(4,1)
C

```



```

C Find out if we grab a new frame or use the existing one.
C
0015      TYPE 1000
0016      1000 FORMAT(10X,'Welcome to PELLET, the ICF Image Processing'//
1          10X,'Program. You can grab a new frame from the'//
1          10X,'TV camera or use one already stored in the'//
1          10X,'Quantex. Type "0" to use an existing frame'//
1          10X,'or "1" to grab a new frame.'//
1          '$',9X,'Grab?')
0017      ACCEPT 1001,KR
0018      IF(KR.NE.1)GO TO 20
0020      CALL CURSOR(4,1)
0021      CALL CLEAR(1)
C
C Obtain the address of subroutine GRAB.
C
0022      CALL GETADR(ICMPLT,GRAB)
C
C Make sure the MNCDO bit 15 is clear.
C
0023      CALL DOUT(0,"1000000,IER,0)
C
C Start of main "Grab" loop...
C
C Set up the IEEE bus and the Quantex interface.
C
0024      1    CALL IBIFC
C
C Now initialize the data buffer and information array.
C
0025      CALL SETIBF(INFO,IND,,IBUF)
0026      IERR=1
0027      IF(IND.NE.1)GO TO 999
0029      CALL RLSBUF(INFO,IND,0)
0030      IERR=2
0031      IF(IND.NE.1)GO TO 999
C
C Set the clock to external mode (ST1).
C
0033      CALL CLOCA(6,-1,IND)
0034      IERR=3
0035      IF(IND.NE.1)GO TO 999
C
C Start the "sweep".
C
0037      CALL ADSWP(INFO,1,1,256,,ICMPLT(1))
C
C Check for successful return.
C
0038      IERR=4
0039      IF(INFO(1).GT.1)GO TO 999
C
C Wait for the completion routine.
C

```

```

0041      CALL SUSPND
C
C Now you can process the stored image.
C
0042      20  CALL CURSOR(4,1)
0043      CALL CLEAR(1)
0044      TYPE 1002
0045      1002 FORMAT(10X,'An image is now ready to be processed. '//
1          10X,'The following processing steps are available. '//
1          15X,'0 - Grab another frame (only alone) '//
1          15X,'1 - Store the current frame on disk '//
1          15X,'2 - Contrast stretch the image '//
1          15X,'3 - Sobel edge enhance the image '//
1          15X,'4 - Smooth the image '//
1          15X,'5 - Apply a binary threshold to image '//
1          15X,'6 - Extract pellet parameters '//
1          10X,'You may enter up to 10 steps to be executed in '//
1          10X,'sequential order. Or you may enter a '0' alone '//
1          10X,'to grab another frame. Parameter extraction, if '//
1          10X,'requested, always terminates the sequence. '//)
0046      2   CALL CURSOR(23,1)
0047      CALL ERASE(1)
0048      CALL BOLD
0049      CALL PUTSTR(5,BEEP,'$')
0050      TYPE 1003
0051      1003 FORMAT('$',9X,'Enter processing sequence:')
0052      ACCEPT 1001,ISTEP
0053      1001 FORMAT(10I5)
0054      CALL NORMAL
0055      IF(ISTEP(1).EQ.0)GO TO 1
0057      DO 5 II=1,10
0058      I=II
0059      IF(ISTEP(I).LT.0)GO TO 2
0061      IF(ISTEP(I).GT.9)GO TO 2
0063      5   CONTINUE
0064      CALL CURSOR(1,5)
0065      CALL PUTSTR(5,'Start','$')
0066      CALL TIME(STIM)
0067      CALL CURSOR(2,4)
0068      CALL PUTSTR(5,STIM,'$')
0069      DO 10 II=1,10
0070      I=II
0071      CALL NORMAL
0072      IF(ISTEP(I).EQ.0)GO TO 11
0074      CALL CURSOR(4,1)
0075      CALL CLEAR(1)
0076      CALL PUTSTR(5,BEEP,'$')
0077      TYPE 1004,I
0078      1004 FORMAT('$',9X,'Step number ',I2,', ')
C
C Now branch to the proper processing step
C
0079      GO TO (100,200,300,600,400,500,2,2,900),ISTEP(I)
C

```

```

0080 100 TYPE 101
0081 101 FORMAT(' Store the current frame on floppy disk. '//)
0082 CALL STORE
0083 GO TO 10
C
0084 200 TYPE 201
0085 201 FORMAT(' Contrast stretch the current image. '//)
0086 CALL STRECH
0087 GO TO 10
C
0088 300 TYPE 301
0089 301 FORMAT(' Sobel edge enhance the current image. '//)
0090 CALL SOBEL
0091 GO TO 10
C
0092 400 TYPE 401
0093 401 FORMAT(' Threshold map the current image. '//)
0094 CALL THRESH
0095 GO TO 10
C
0096 500 TYPE 501
0097 501 FORMAT(' Extract pellet parameters from image. '//)
0098 CALL PARAMS
0099 GO TO 11
C
0100 600 TYPE 601
0101 601 FORMAT(' Smooth the image. '//)
0102 CALL SMOOTH
0103 GO TO 10
C
0104 900 TYPE 901
0105 901 FORMAT(' Restore an image from disk. '//)
0106 CALL RESTOR
0107 GO TO 10
C
0108 10 CONTINUE
0109 11 TYPE 1010
0110 1010 FORMAT(10X, 'End of Processing sequence. '//)
0111 CALL CSAVE
0112 CALL CURSOR(1,60)
0113 CALL PUTSTR(5, 'Finish', '$')
0114 CALL TIME(STIM)
0115 CALL CURSOR(2,59)
0116 CALL PUTSTR(5, STIM, '$')
0117 CALL SCROLL(1,1)
0118 CALL CREST
0119 CALL EXIT
C
C Error processing...
C
0120 999 CALL CURSOR(4,1)
0121 CALL CLEAR(1)
0122 TYPE 9001, IERR, IND, INFO(1)
0123 9001 FORMAT('Error code = ', I5/

```



```
1      / IND      = ',I5/  
2      / INFO(1)  = ',I5/)
```

C

C If the error is "data overrun", it is ignored and we

C Just try again.

C

```
0124      IF(INFO(1).EQ.313)GO TO 1
```

C

C Any other error causes program termination!

C

```
0126      GO TO 11
```

```
0127      END
```

STORE

```

0001      SUBROUTINE STORE
C
C STORE.FOR      Version 01      17-Mar-79      BAB
C
C THIS SUBROUTINE READS THE MEMORY OF THE QUANTEX DS-12F VIDEO
C FRAME GRABBER AND STORES THE DIGITIZED FRAME ON FLOPPY DISK.
C
0002      BYTE CMND(20),FRAME(256),SAVE(4),FILNAM(20)
0003      DATA SAVE/4*0/,FRAME/256*0/
0004      DATA CMND/1,61,34,
1 2,32,48,64,80,96,
2 3,47,63,79,95,111,
3 15,
4 0,0,0,0/
0005      CALL IBIFC
0006      CALL IBTERM
0007      TYPE 275
0008 275  FORMAT('$',14X,'Enter name of output ')
0009      CALL FILE(FILNAM,'.DAT',IERR)
0010      IF(IERR.NE.0)STOP 'FILE ERROR'
0012      CALL ASSIGN(1,FILNAM,0,'NEW')
0013      DEFINE FILE 1(256,128,U,N1)
0014      CALL IBSEND(CMND,-1,4)
0015      CALL IBARCV(FRAME,256,4)
0016      DO 410 I=1,256
0017      II=I
0018      LEND=IBWAIT()
0019      SAVE(1)=FRAME(256)
0020      DO 300 J=256,2,-1
0021      FRAME(J)=FRAME(J-1)
0022 300  CONTINUE
0023      FRAME(1)=SAVE(2)
0024      WRITE(1'II)FRAME
0025      IF(I.EQ.256)GO TO 411
0027      CALL IBARCV(FRAME,256)
0028      SAVE(2)=SAVE(1)
0029 410  CONTINUE
0030 411  READ(1'1)FRAME
0031      FRAME(1)=SAVE(1)
0032      FRAME(2)=SAVE(2)
0033      WRITE(1'1)FRAME
0034      CALL CLOSE(1)
0035      RETURN
0036      END

```


STRECH

```

0001      SUBROUTINE STRECH
C
C STRECH.FOR      Version 01      17-Mar-79      BAB
C
C This program is an updated version of ENHANC.FOR.
C It has been modified to perform contrast stretching
C in the Quantex rather than on disk files containing
C previously stored images. It uses subroutines GETLIN
C and PUTLIN.
C
0002      INTEGER*2 IHIST(256)
0003      BYTE LINE(256)
0004      DATA LINE/256*0/,IHIST/256*0/
0005      CALL IBTERM()
0006      IMAX=0
0007      IMIN=255
0008      TYPE 1003
0009 1003  FORMAT('$',14X,'Enter top and bottom lines to check:')
0010      ACCEPT 1004,L0,L1
0011 1004  FORMAT(2I5)
0012      TYPE 1005
0013 1005  FORMAT('$',14X,'Enter left and right columns to check:')
0014      ACCEPT 1004,M0,M1
0015      PIX=FLOAT(L1-L0+1)*FLOAT(M1-M0+1)
0016      IF(PIX.EQ.0)PIX=256.**2
0018      SUM=0.0
0019      NZ=0
0020      NS=0
0021      DO 410 I=L0,L1
0022      II=I
0023      CALL GETLIN(II,LINE)
0024      DO 400 J=M0,M1
0025      IVAL=LINE(J)
0026      IF(IVAL.EQ.0)NZ=NZ+1
0028      IF(IVAL.LT.0)IVAL=IVAL+256
0030      IF(IVAL.EQ.255)NS=NS+1
0032      SUM=SUM+IVAL
0033      IHIST(IVAL+1)=IHIST(IVAL+1)+1
0034      IF(IVAL.GT.IMAX)IMAX=IVAL
0036      IF(IVAL.LT.IMIN)IMIN=IVAL
0038 400   CONTINUE
0039 410   CONTINUE
0040      SUMM=0.0
0041      DO 450 I=1,256
0042      SUMM=SUMM+IHIST(I)
0043      IF(SUMM.GT.PIX/2.)GO TO 460
0045 450   CONTINUE
0046 460   MEDIAN=I-1
0047      AVE=SUM/PIX
0048      TYPE 1008,IMIN,IMAX,AVE,MEDIAN
0049 1008  FORMAT('0',14X,'Image Statistics:'/20X,' Minimum Pixel = ',I5/
1 20X,' Maximum Pixel = ',I5/20X,' Average value = ',F7.1/
1 20X,' Median value = ',I5/)
0050      IF(NZ.NE.0)TYPE 1009,NZ

```

```

0052      IF(NS.NE.0)TYPE 1010,NS
0054      1009 FORMAT('0',9X,'WARNING: Number of zero pixels      = ',I6)
0055      1010 FORMAT('0',9X,'WARNING: Number of saturated pixels = ',I6)
C
C NOW FIND A FACTOR TO EXPAND THE DYNAMIC RANGE BY...
C
0056      DO 500 I=1,256
0057      II=I
0058      CALL GETLIN(II,LINE)
0059      DO 510 J=1,256
0060      VAL=LINE(J)
0061      IF(VAL.LT.0)VAL=VAL+256.
0063      XM=255./FLOAT(IMAX-IMIN)
0064      VAL=XM*(VAL-IMIN)
0065      IF(VAL.LT.0.0)VAL=0.0
0067      IF(VAL.GT.255.0)VAL=255.0
0069      510  LINE(J)=VAL
0070      CALL PUTLIN(II,LINE)
0071      500  CONTINUE
0072      RETURN
0073      END

```


SOBEL

```

0001      SUBROUTINE SOBEL
C
C SOBEL.FOR      Version 01      17-Mar-80      BAB
C
C This subroutine implements the Sobel edge enhancement algorithm
C in the Quantex memory rather than on a disk file containing
C the digitized image. This program is being used to study the
C advantages to doing image processing in the Quantex.
C
0002      BYTE RCMND(20),WCMND(20),SAVE(2)
0003      BYTE PBUFF(8192),QBUFF(8192)
0004      BYTE PBUFF1(4096),QBUFF1(4096)
0005      BYTE SLICE(3,256),LINE(256)
0006      EQUIVALENCE (PBUFF(1),QBUFF(2))
0007      EQUIVALENCE (PBUFF1(1),PBUFF(4097))
0008      EQUIVALENCE (QBUFF1(1),QBUFF(4097))
0009      DATA SAVE/0,0/
C
C The following DATA statements initialize the READ and WRITE
C commands which are sent via the GPIB to the Quantex
C
0010      DATA RCMND/1,61,34,
1 2,32,48,64,80,96,
2 3,32,48,64,81,96,
3 15,
4 0,0,0,0/
0011      DATA WCMND/1,49,34,
1 2,32,48,64,80,96,
2 3,32,48,64,81,96,
3 15,
4 0,0,0,0/
C
C Enter the threshold to be used for the edge map...
C
0012      CALL IBIFC      !master bus clear
0013      CALL IBTERM     !disable record terminators
C
C Read in an initial buffer of image data (8k bytes)
C
0014      TSTART=SECNDS(0.0)
0015 1    CALL IBIFC      !master bus clear
0016      RCMND(14)=82      !this read 20000(8) bytes
0017      CALL IBASND(RCMND,-1,4)      !send READ command
0018      CALL IBRECV(PBUFF,8192,4)      !receive response
0019      RCMND(8)=RCMND(8)+2      !next read from 20000(8)
0020      RCMND(14)=81      !next read 10000(8) bytes
0021      SAVE(1)=PBUFF(8192)
C
C Call the SOBEL routine on the initial buffer...
C
0022      DO 110 J=1,256
0023      SLICE(1,J)=QBUFF(J)
0024      SLICE(2,J)=QBUFF(J)
0025 110  SLICE(3,J)=QBUFF(J+256)

```

```

0026      DO 130 I=2,31
0027      CALL SOBELA(SLICE,LINE)
0028      N=I*256
0029      NO=(I-2)*256
0030      DO 130 J=1,256
0031      SLICE(1,J)=SLICE(2,J)
0032      SLICE(2,J)=SLICE(3,J)
0033      SLICE(3,J)=QBUFF(N+J)
0034      130 QBUFF(NO+J)=LINE(J)
C
C Now output the top half of the modified buffer (4K)
C
0035      CALL IBIFC                      !master bus clear
0036      CALL IBASND(WCMND,-1,4)         !send WRITE cmdnd
0037      CALL IBSEDI(QBUFF,4096,4)      !send data + EOI
0038      WCMND(8)=WCMND(8)+1             !update the address
C
C Enter the loop to process the whole frame
C
0039      DO 100 K=2,16
C
C Now shove the second half of the buffer up to the top
C and fill the bottom half with new data. Watch out for the
C missing first two pixels!
C
0040      DO 140 J=1,4096
0041      QBUFF(J)=QBUFF1(J)
0042      140 CONTINUE
0043      QBUFF1(1)=SAVE(1)
0044      CALL IBIFC                      !master bus clear
0045      CALL IBASND(RCMND,-1,4)         !send READ command
0046      CALL IBRECV(PBUFF1,4096,4)    !receive next buffer
0047      SAVE(1)=PBUFF1(4096)
C
C Call SOBEL to process the remainder of the buffer
C
0048      DO 230 I=16,31
0049      CALL SOBELA(SLICE,LINE)
0050      N=I*256
0051      NO=(I-2)*256
0052      DO 230 J=1,256
0053      SLICE(1,J)=SLICE(2,J)
0054      SLICE(2,J)=SLICE(3,J)
0055      SLICE(3,J)=QBUFF(N+J)
0056      QBUFF(NO+J)=LINE(J)
0057      230 CONTINUE
C
C Once again output the top half of the buffer
C
0058      CALL IBIFC                      !master bus clear
0059      CALL IBASND(WCMND,-1,4)         !send write command
0060      CALL IBSEDI(QBUFF,4096,4)      !send the top buffer
C
C Update the addresses and do it again, until the screen is full

```



```

C
0061      RCMND(8)=RCMND(8)+1
0062      WCMND(8)=WCMND(8)+1
0063      100  CONTINUE
0064      TEND=SECNDS(TSTART)
0065      TYPE 440,TEND
0066      440  FORMAT('0          Elapsed time = ',F10.1,' seconds. '//)
0067      RETURN
0068      END

```

SOBELA

```

0001      SUBROUTINE SOBELA(SLICE,LINE)
C
C This routine does Sobel edge detection on slices of digital image data.
C
C The data is input through a 3x256 array, containing three lines
C of video frame data. It is up to the calling program to make sure
C that the input array contains the correct lines from the input image.
C The output array, dimensioned 256 contains the resultant values
C for the line of interest. That is the line input in the second
C row of the input array.
C
0002      INTEGER IVA(8)
0003      BYTE SLICE(3,256),LINE(256)
C
C Now generate the new line...
C
0004      DO 100 J=2,255
0005          IVA(1)=SLICE(1,J-1)
0006          IVA(2)=SLICE(1,J)
0007          IVA(3)=SLICE(1,J+1)
0008          IVA(4)=SLICE(2,J+1)
0009          IVA(5)=SLICE(3,J+1)
0010          IVA(6)=SLICE(3,J)
0011          IVA(7)=SLICE(3,J-1)
0012          IVA(8)=SLICE(2,J-1)
0013          DO 110 IV=1,8
0014              IF(IVA(IV).LT.0) IVA(IV)=IVA(IV)+256
0016      110      CONTINUE
0017              T1=IVA(3)+2*IVA(4)+IVA(5)
0018              T2=IVA(1)+2*IVA(8)+IVA(7)
0019              T3=IVA(1)+2*IVA(2)+IVA(3)
0020              T4=IVA(7)+2*IVA(6)+IVA(5)
0021              X=T1-T2
0022              Y=T3-T4
0023              G=SQRT(X**2+Y**2)
0024              IVA(1)=IFIX(G+0.499999)
0025              IF(IVA(1).LT.0) IVA(1)=0
0027              IF(IVA(1).GT.255) IVA(1)=255
0029              LINE(J)=IVA(1)
0030      100      CONTINUE
0031              LINE(1)=SLICE(2,1)
0032              LINE(256)=SLICE(2,256)
0033              RETURN
0034              END

```


SMOOTH

```

0001      SUBROUTINE SMOOTH
C
C SMOOTH.FOR      Version 01      24-Mar-80      BAB
C
C This subroutine smooths the image in the Quantex by
C replacing a given pixel by the average of the surrounding
C eight pixels.
C
0002      INTEGER*2 IVA(9)
0003      BYTE LINE1(256),LINE2(256),LINE3(256),FRAM(256)
C
C Here we examine the eight pixels surrounding
C of the pixel of interest. We compute the new value of the pixel
C from the average of the surrounding pixels.
C
0004      CALL GETLIN(1,LINE1)
0005      CALL GETLIN(2,LINE2)
C
C The big loop from here to 500 does the smoothing.
C
0006      DO 500 I=3,256
0007          II=I
0008          CALL GETLIN(II,LINE3)
C
0009      DO 510 J=2,255
0010          IVA(1)=LINE1(J-1)
0011          IVA(2)=LINE2(J)
0012          IVA(3)=LINE1(J+1)
0013          IVA(4)=LINE2(J+1)
0014          IVA(5)=LINE3(J+1)
0015          IVA(6)=LINE3(J)
0016          IVA(7)=LINE3(J-1)
0017          IVA(8)=LINE2(J-1)
0018          IVA(9)=LINE2(J)
0019          SUM=0.0
C
0020      DO 520 IV=1,9
0021          IF(IVA(IV).LT.0) IVA(IV)=IVA(IV)+256
0022          SUM=SUM+IVA(IV)
0023
0024 520      CONTINUE
C
0025      SUM=SUM+IVA(9)
0026      IVA(1)=SUM/10.0
0027      IF(IVA(1).LT.0) IVA(1)=0
0028      IF(IVA(1).GT.255) IVA(1)=255
0029
0030 510      FRAM(J)=IVA(1)
C
0031
0032      FRAM(1)=LINE2(1)
0033      FRAM(256)=LINE2(256)
0034      II=II-1
0035      CALL PUTLIN(II,FRAM)
C
0036      DO 500 J=1,256
0037          LINE1(J)=LINE2(J)

```

```
038      LINE2(J)=LINE3(J)
0039      500  CONTINUE
      C
0040      RETURN
0041      END
```


THRESH

```

0001      SUBROUTINE THRESH
C
C THRESH.FOR      Version 02      25-Mar-79      BAB
C
C This thresholding routine uses the statistical section from
C STRECH to compute the mean and median of a group of pixels.
C Once the statistics are computed, it requests a threshold
C value. The operator can make an intelligent response aided
C by the statistics.
C
0002      INTEGER*2 IHIST(256)
0003      BYTE LINE(256)
0004      DATA LINE/256*0/,IHIST/256*0/
0005      CALL IBTERM()
0006      IMAX=0
0007      IMIN=255
0008      TYPE 1000
0009 1000  FORMAT('$',14X,'Enter top and bottom lines to check:')
0010      ACCEPT 1001,L0,L1
0011 1001  FORMAT(2I5)
0012      TYPE 1002
0013 1002  FORMAT('$',14X,'Enter left and right columns to check:')
0014      ACCEPT 1001,M0,M1
0015      PIX=FLOAT(L1-L0+1)*FLOAT(M1-M0+1)
0016      IF(PIX.EQ.0)PIX=256.**2
0018      SUM=0.0
0019      NZ=0
0020      NS=0
0021      DO 110 I=L0,L1
0022      II=I
0023      CALL GETLIN(II,LINE)
0024      DO 100 J=M0,M1
0025      IVAL=LINE(J)
0026      IF(IVAL.EQ.0)NZ=NZ+1
0028      IF(IVAL.LT.0)IVAL=IVAL+256
0030      IF(IVAL.EQ.255)NS=NS+1
0032      SUM=SUM+IVAL
0033      IHIST(IVAL+1)=IHIST(IVAL+1)+1
0034      IF(IVAL.GT.IMAX)IMAX=IVAL
0036      IF(IVAL.LT.IMIN)IMIN=IVAL
0038 100   CONTINUE
0039 110   CONTINUE
0040      SUMM=0.0
0041      DO 150 I=1,256
0042      SUMM=SUMM+IHIST(I)
0043      IF(SUMM.GT.PIX/2.)GO TO 160
0045 150   CONTINUE
0046 160   MEDIAN=I-1
0047      AVE=SUM/PIX
0048      TYPE 1004,IMIN,IMAX,AVE,MEDIAN
0049 1004  FORMAT('0',14X,'Image Statistics:'/20X,' Minimum pixel = ',I5/
1 20X,' Maximum pixel = ',I5/20X,' Average value = ',F7.1/
1 20X,' Median value = ',I5/)
0050      IF(NZ.NE.0)TYPE 1005,NZ

```

```

0052      IF(NS.NE.0)TYPE 1006,NS
0054      1005 FORMAT('0',14X,'Number of zero pixels      = ',I6)
0055      1006 FORMAT('0',14X,'Number of saturated pixels = ',I6)
C
C This routine applies a binary thrshold to the image stored
C in the digital image memory (Quantex DS-12F). All pixels
C below ICUT are made equal to 0 (black) and all pixels
C above ICUT are made equal to 255 (white).
C
0056      TYPE 1007
0057      1007 FORMAT('$',14X,'Enter threshold cutoff value (0-255):')
0058      ACCEPT 1001,ICUT
0059      DO 200 II=1,256
0060      I=II
0061      CALL GETLIN(I,LINE)
0062      DO 300 JJ=1,256
0063      J=JJ
0064      IPIX=LINE(J)
0065      IF(IPIX.LT.0)IPIX=IPIX+256
0067      JPIX=0
0068      IF(IPIX.GE.ICUT)JPIX=255
0070      300 LINE(J)=JPIX
0071      CALL PUTLIN(I,LINE)
0072      200 CONTINUE
0073      RETURN
0074      END

```

PARAMS


```

0001      SUBROUTINE PARAMS
C
C PARAMS.FOR      Version 01      20-Mar-80      BAB
C
C This subroutine is used to process enhanced images of
C ICF pellets. It is used after Sobel edge enhancement
C and the edge map generation. It determines the following
C parameters of the image...
C
C   1) The apparent center of the pellet in the image field
C
C   2) The average diameter of the pellet as determined
C       from measurements in the x and y directions
C
C   3) The gross out-of-round difference between the x and
C       y diameter measurements
C
C Restrictions and usage...
C
C   1) The pellet image must cover coordinate (128,128) in
C       the frame grabber memory
C
C   2) The image to be processed must be a white on black
C       edge map of the original image
C
C   3) For best results, the edge map should have no gaps,
C       nor should there be any structure inside the pellet
C       perimeter.
C
C -----
C Find the center of the pellet...
C
C   NOTE: All variables beginning with "I" designate
C   x-coordinate values (horizontal axis). "J" variables
C   designate y-coordinate values (vertical axis). That means
C   that "J" quantities measure lines and "I" values measure
C   pixels within a line.
C
C   The versions of GETPIX and PUTPIX used are the ones which
C   are in files GETPXY and PUTPXY. The arguments are the x- and
C   y-coordinates, not the line and column numbers.
C
C START
C
0002      CALL CURSOR(6,1)
0003      TYPE 1100
0004      1100 FORMAT(10X,'First order estimate of pellet parameters...')
0005      CALL CURSOR(8,1)
0006      CALL CLEAR(1)
0007      ICT=128
0008      JCT=128
0009      TYPE 1000,ICT,JCT
0010      1000 FORMAT(15X,'Coordinates of center - (',I3,',',I3,') *ESTIMATE*')

```

```

0011 1010 FORMAT(15X,'Coordinates of center - (',I3,',',I3,')')
      C
      C From here to line 140, we correct the y-coordinate of the center.
      C
0012 10 ICT0=ICT
0013 JCT0=JCT
0014 CALL PUTPIX(ICT,JCT,255)
      C
      C Loops 100 and 105 scan vertically from center upward.
      C
0015 DO 100 JJ=JCT-1,0,-1
0016 JY=JJ
0017 CALL GETPIX(ICT,JY,IVAL)
0018 IF(IVAL.NE.0)GO TO 110
0020 100 CONTINUE
0021 110 J1=JY
0022 IF(JY.EQ.0)GO TO 107
      C
      C Loop 105 scans for outside of edge.
      C
0024 DO 105 JJ=J1-1,0,-1
0025 JY=JJ
0026 CALL GETPIX(ICT,JY,IVAL)
0027 IF(IVAL.EQ.0)GO TO 107
0029 105 CONTINUE
0030 107 J2=JY
0031 IF(J2.EQ.J1-1)J2=J1
      C
      C JTOP is the top edge of the pellet found this time.
      C
0033 JTOP=JCT-(J1+J2)/2
      C
      C Loops 120 and 125 scan from the center downward.
      C
0034 DO 120 JJ=JCT+1,255
0035 JY=JJ
0036 CALL GETPIX(ICT,JY,IVAL)
0037 IF(IVAL.NE.0)GO TO 130
0039 120 CONTINUE
0040 130 J1=JY
0041 IF(JY.EQ.255)GO TO 127
0043 DO 125 JJ=J1+1,255
0044 JY=JJ
0045 CALL GETPIX(ICT,JY,IVAL)
0046 IF(IVAL.EQ.0)GO TO 127
0048 125 CONTINUE
0049 127 J2=JY
      C
      C JBOT is the bottom edge found this time.
      C
0050 JBOT=(J1+J2)/2 - JCT
0051 JDIF=JBOT-JTOP
0052 CALL PUTPIX(ICT,JCT,0)
0053 IF(IABS(JDIF).LE.1)GO TO 140

```

```

C
C JCT is now the new estimate of the center y-coordinate.
C
0055      JCT=JCT+JDIF/2
0056      CALL CURSOR(8,1)
0057      TYPE 1000,ICT,JCT
0058      140  CONTINUE
0059      CALL PUTPIX(ICT,JCT,255)
C
C Now we correct the estimate of the center x-coordinate.
C
C Loops 200 and 205 scan from the center leftward.
C
0060      DO 200 II=ICT-1,0,-1
0061      IX=II
CT,IQ,0)GO TO 207
0074      205  CONTINUE
0075      207  I2=IX
0076      IF(I2.EQ.I1-1)I2=I1
C
C ILEFT is the leftmost edge of the pellet on this line.
C
0078      ILEFT=ICT-(I1+I2)/2
C
C Loops 220 and 225 scan from the center rightward.
C
0079      DO 220 II=ICT+1,255
0080      IX=II
0081      CALL GETPIX(IX,JCT,IVAL)
0082      IF(IVAL.NE.0)GO TO 230
0084      220  CONTINUE
0085      230  I1=IX
0086      IF(I1.EQ.255)GO TO 227
0088      DO 225 II=I1+1,255
0089      IX=II
0090      CALL GETPIX(IX,JCT,IVAL)
0091      IF(IVAL.EQ.0)GO TO 227
0093      225  CONTINUE
0094      227  I2=IX
C
C IRIGHT is the rightmost edge on this line.
C
0095      IRIGHT=(I1+I2)/2 -ICT
0096      IDIF=IRIGHT-ILEFT
0097      CALL PUTPIX(ICT,JCT,0)
0098      IF(IABS(IDIF).LE.1)GO TO 240

```

```

C
C ICT is the new estimate of the x-coordinate of center.
C
0100     ICT=ICT+IDIF/2
0101     CALL CURSOR(8,1)
0102     TYPE 1000,ICT,JCT
0103     240 CONTINUE
C
C If the coordinates have converged on a point, so back
C and correct them assain. If they have, print the results.
C
0104     IF(ICT.NE.ICT0)GO TO 10
0106     IF(JCT.NE.JCT0)GO TO 10
C
C Now compute the apparent diameters along both axes and the
C average diameter. Then compute the "out-of-roundness."
C
0108     CALL CURSOR(8,1)
0109     CALL ERASE(1)
0110     TYPE 1010,ICT,JCT
0111     XDIA=ILEFT+IRIGHT
0112     YDIA=JBOT+JTOP
0113     AVDIAM=(XDIA+YDIA)/2.0
0114     AVRAD=AVDIAM/2.0
0115     OUT=ABS(XDIA-YDIA)
0116     CALL CURSOR(10,1)
0117     TYPE 1001,XDIA,YDIA,AVDIAM,OUT
0118     1001 FORMAT(15X,'Horizontal dimension = ',F6.1,' pixels'//
1         15X,'Vertical dimension   = ',F6.1,' pixels'//
1         15X,'Average diameter     = ',F6.1,' pixels'//
1         15X,'Out-of-roundness    = ',F6.1,' pixels'//)
C
C Request the calibration factor...
C
0119     CALL CURSOR(20,1)
0120     TYPE 1011
0121     1011 FORMAT('$',14X,'Enter calibration factor in microns/pixel:')
0122     ACCEPT 1012,FACT
0123     1012 FORMAT(F10.0)
0124     XDIA=XDIA*FACT
0125     YDIA=YDIA*FACT
0126     AVDIAM=AVDIAM*FACT
0127     OUT=OUT*FACT
0128     CALL CURSOR(10,1)
0129     TYPE 1013,XDIA,YDIA,AVDIAM,OUT
0130     1013 FORMAT(15X,'Horizontal dimension = ',F6.1,' microns'//
1         15X,'Vertical dimension   = ',F6.1,' microns'//
1         15X,'Average diameter     = ',F6.1,' microns'//
1         15X,'Out-of-roundness    = ',F6.1,' microns'//)
0131     CALL CLEAR(1)
0132     RETURN
0133     END

```


RESTOR

```

0001      SUBROUTINE RESTOR
C
C RESTOR.FOR      VERSION 01      17-MAY-79      BAB
C
C THIS PROGRAM READS A FILE FROM THE FLOPPY DISK
C AND RESTORES THE DIGITIZED FRAME TO THE FRAME GRABBER
C
0002      BYTE CMND(20),FRAME(256),FILNAM(20)
0003      DATA CMND/1,49,34,
1 2,32,48,64,80,96,
3 15,
4 0,0,0,0,0,0,0,0,0,0/
0004      CALL IBIFC
0005      CALL IBTERM
0006      TYPE 275
0007 275  FORMAT('$',14X,'Enter the name of the Input ')
0008      CALL FILE(FILNAM,'.DAT',IERR)
0009      IF(IERR.NE.0)STOP 'FILE ERROR'
0011      CALL ASSIGN(1,FILNAM,0,'RO')
0012      DEFINE FILE 1(256,128,U,N1)
0013      CALL IBSEND(CMND,-1,4)
0014      DO 410 I=1,256
0015      II=I
0016      READ(1,II)FRAME
0017      CALL IBSEND(FRAME,256,4)
0018 410  CONTINUE
0019      CALL IBSEDI(0,1,4)
0020      CALL CLOSE(1)
0021      RETURN
0022      END

```

CALIBR

```

C CALIBR.FOR          Version 02          19-Mar-79          BAB
C
C This program is based loosely on the old GRALIN program.
C Cursors can be placed anywhere in the display and
C values at the cursors read out.
C
C This program uses GETLIN to read lines of video data.
C

```

```

0001      BYTE FRAM(256),CURS(256)
0002      DATA CURS/256*-1/
0003      CALL CLEAR(0)
0004      CALL BOLD
0005      CALL REVERS
0006      CALL CURSOR(1,20)
0007      CALL PUTSTR(5,' ICF Pellet Characterization ',0)
0008      CALL CURSOR(2,20)
0009      CALL PUTSTR(5,' Calibration Procedure ',0)
0010      CALL NORMAL
0011      CALL SCROLL(13,24)
0012      CALL CURSOR(13,1)

```

```

C
C Section 1. Horizontal calibration.
C

```

```

0013      TYPE 1000
0014      1000 FORMAT(5X,'1. Horizontal Calibration -- Insert calibration slide'/
1 5X,'at focal plane with graticule in horizontal position.'//
1 '$',4X,'Type <CR> when ready to grab image.')
0015      ACCEPT 1001,KR
0016      1001 FORMAT(I5)
C      CALL GRAB
C

```

```

C We pick out a line by moving a cursor up or down
C

```

```

0017      CALL CURSOR(13,1)
0018      CALL CLEAR(1)
0019      TYPE 1002
0020      1002 FORMAT(5X,'2. Use the arrow keys to position the line cursor on'/
1 5X,'the line to be measured. UP and DOWN give fine motion'/
1 5X,'LEFT and RIGHT give coarse motion.'//
1 '$',4X,'Type <CR> when ready.')
0021      LINE=128
0022      3      CALL GETLIN(LINE,FRAM)
0023      CALL PUTLIN(LINE,CURS)
0024      5      ICMD=IGTCMD()
0025      CALL PUTLIN(LINE,FRAM)
0026      IF(ICMD,EQ,-1)GO TO 7
0028      IF(ICMD,EQ,0)GO TO 999
0030      IF(ICMD,EQ,1)LINE=LINE-1
0032      IF(ICMD,EQ,2)LINE=LINE+1
0034      IF(ICMD,EQ,4)LINE=LINE-10
0036      IF(ICMD,EQ,3)LINE=LINE+10
0038      IF(LINE,LT,16)LINE=16
0040      IF(LINE,GT,256)LINE=256
0042      GO TO 3

```



```

0043 7    CALL CURSOR(5,1)
0044     TYPE 1007,LINE
0045 1007 FORMAT(10X,'Line being measured ',I4)
C
C First enter the left cursor, then the right...
C
0046     CALL CURSOR(13,1)
0047     CALL CLEAR(1)
0048     TYPE 1003
0049 1003 FORMAT(5X,'3. Use the arrow keys to place the pixel cursor'//
1 5X,'on the left-most graticule line to be measured.'//
1 5X,'LEFT and RIGHT give fine motion, UP and DOWN give'//
1 5X,'coarse motion.'//
1 '$',4X,'Type <CR> when ready.')
0050     IL=0
0051 30    IPIX=128
0052     CALL PIXEL(LINE,IPIX,IVAL,0)
0053 35    CALL PIXEL(LINE,IPIX,IVAL,1)
0054 40    ICMD=IGTCMD() !set the cursor command
0055     IF(ICMD.EQ.0)GO TO 40
0057     IF(ICMD.EQ.-1)GO TO 45
0059     IF(ICMD.EQ.1)IPIX=IPIX-10
0061     IF(ICMD.EQ.2)IPIX=IPIX+10
0063     IF(ICMD.EQ.3)IPIX=IPIX+1
0065     IF(ICMD.EQ.4)IPIX=IPIX-1
0067     IF(IPIX.LT.0)IPIX=0
0069     IF(IPIX.GT.255)IPIX=255
0071     GO TO 35
0072 45    IF(IL.EQ.1)GO TO 50
0074     IL=1
0075     ILEFT=IPIX
0076     KLEFT=IVAL
0077     CALL CURSOR(6,1)
0078     TYPE 1004,ILEFT
0079 1004 FORMAT(10X,'Left marker at pixel ',I4)
0080     CALL CURSOR(13,1)
0081     CALL CLEAR(1)
0082     TYPE 1005
0083 1005 FORMAT(5X,'4. Use the arrow keys to place the pixel cursor'//
1 5X,'on the right-most graticule line to be measured.'//
1 5X,'LEFT and RIGHT give fine motion, UP and DOWN give'//
1 5X,'coarse motion.'//
1 '$',4X,'Type <CR> when ready.')
0084     GO TO 30
0085 50    IRIGHT=IPIX
0086     KRIGHT=IVAL
0087     CALL CURSOR(7,1)
0088     TYPE 1006,IRIGHT
0089 1006 FORMAT(10X,'Right marker at pixel ',I4)
0090     CALL CURSOR(13,1)
0091     CALL CLEAR(1)
0092     TYPE 1008
0093 1008 FORMAT('$',4X,'5. Enter the distance between the markers ',
1 'in microns:')

```

```

0094      ACCEPT 1009,HDIST
0095 1009  FORMAT(F10.0)
0096      HCAL=HDIST/IABS(IRIGHT-ILEFT)
0097      CALL CURSOR(9,1)
0098      TYPE 1010,HCAL
0099 1010  FORMAT(10X,'Horizontal calibration = ',F6.2,' microns/pixel.')
0100      CALL PUTPIX(ILEFT,LINE,KLEFT)
0101      CALL PUTPIX(IRIGHT,LINE,KRIGHT)
0102      CALL CURSOR(13,1)
0103      CALL CLEAR(1)
0104      TYPE 1011
0105 1011  FORMAT('$',4X,'Type <CR> to exit program.')
0106      ACCEPT 1001,KR
C
0107 999   CALL NORMAL
0108      CALL SCROLL(1,24)
0109      CALL CURSOR(1,1)
0110      CALL CLEAR(0)
0111      STOP
0112      END

```

```

0001      INTEGER FUNCTION IGT CMD()
0002      DATA IESC/'33/,ILBR/'133/,IA/'101/,IB/'102/,IC/'103/,ID/'104/
0003      IGT CMD=0
0004      JSW=IPEEK('44)
0005      JSW=JSW.OR.'10020      !special TTY mode with ESC proc
0006      CALL IPOKE('44,JSW)
0007      ICHAR=ITTINR()
0008      IF(IC HAR.NE.IESC)GO TO 12
0010      ICHAR=ITTINR()
0011      IF(IC HAR.NE.ILBR)GO TO 10
0013      ICHAR=ITTINR()
0014      IF(IC HAR.EQ.IA)IGT CMD=1      !up
0016      IF(IC HAR.EQ.IB)IGT CMD=2      !down
0018      IF(IC HAR.EQ.IC)IGT CMD=3      !right
0020      IF(IC HAR.EQ.ID)IGT CMD=4      !left
0022      GO TO 10
0023      12      IF(IC HAR.EQ.'15)IGT CMD=-1
0025      10      JSW=IPEEK('44)
0026      JSW=JSW.AND.'167717
0027      CALL IPOKE('44,JSW)
0028      RETURN
0029      END

```

PIXEL


```

0001      SUBROUTINE PIXEL(IPL,IPC,IVAL,IRST)
C
C PIXEL.FOR          VERSION 01          30-MAY-79          BAB
C
C This subroutine addresses an individual pixel, reads its value,
C and makes it either black or white, depending on its true value.
C This routine is useful for implementing a movable cursor in the
C Quantex video memory.
C
C Usage:
C      CALL PIXEL(IPL,IPC,IVAL,IRST)
C
C Where:
C      IPL -- the line number to be addressed (0-255)
C      IPC -- the column number to be addressed (0-255)
C      IVAL -- the value of the pixel returned
C      IRST -- restore parameter, where...
C              0 = don't restore previous pixel
C              1 = restore previous before addressing next
C              2 = restore previous, then return
C
C The value of the pixel to be restored must be in IVAL. The previous
C address is retained. If this routine is being used as a cursor
C generator, IRST has the following effect:
C
C      IRST = 0... This should be the value for the first call.
C                   IVAL will contain the value to be used for
C                   subsequent restorations. If IRST=0 again,
C                   the addressed pixels will remain in their
C                   latched state, the true values are lost.
C      IRST = 1... The addressed pixel will move from location
C                   to location, true values remain in place.
C      IRST = 2... The 'cursor' will be erased, the image is
C                   restored to its original form.
C
0002      BYTE RCMND(10),WCMND(12)
0003      DATA RCMND/1,61,42,
1 2,32,48,64,80,96,
3 15/
0004      DATA WCMND/1,49,42,
1 2,32,48,64,80,96,
3 15,0,0/
0005      CALL IBIFC
0006      CALL IBSDC(4)
0007      CALL IBTERM
0008      CALL IBTIMO(120)
C
C Get the address of the pixel to be read from the keyboard...
C
0009      IF(IRST.EQ.0)GO TO 10
0011      WCMND(11)=IVAL
0012      WCMND(12)=IVAL
D      TYPE 1901,WCMND
D1901  FORMAT(1X,12I5)
0013      CALL IBIFC

```

```

0014      CALL IBSEDI(WCMND,12,4)
0015      IF(IRST.EQ.2)RETURN
0017  10    ILO=IPL.AND."17
0018      IL1=(IPL.AND."360)/16
0019      ICO=IFC.AND."17
0020      IC1=(IFC.AND."360)/16
0021      RCMND(5)=32+ICO
0022      RCMND(6)=48+IC1
0023      RCMND(7)=64+ILO
0024      RCMND(8)=80+IL1
0025      WCMND(5)=RCMND(5)
0026      WCMND(6)=RCMND(6)
0027      WCMND(7)=RCMND(7)
0028      WCMND(8)=RCMND(8)

      C
      C Send the messase to read the pixel...
      C
      D      TYPE 1901,RCMND
0029      CALL IBIFC
0030      CALL IBSEND(RCMND,10,4)
0031      CALL IBRECV(IVAL,1,4)

      C
      C Now send a black or white level to the addressed pixel...
      C
0032      IF(IVAL.GE.128)WCMND(11)=0
0034      IF(IVAL.LT.128)WCMND(11)=255
0036      WCMND(12)=WCMND(11)
      D      TYPE 1901,WCMND
0037      CALL IBIFC
0038      CALL IBSEDI(WCMND,12,4)
0039      RETURN
0040      END

```

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