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DOE'S NEAR-TERM ELECTRIC VEHICLE BATTERY PROGRAM-STATUS OF IMPROVED LEAD-ACID, NICKEL/IRON, AND NICKEL/ZINC BATTERY DEVELOPMENTS

by

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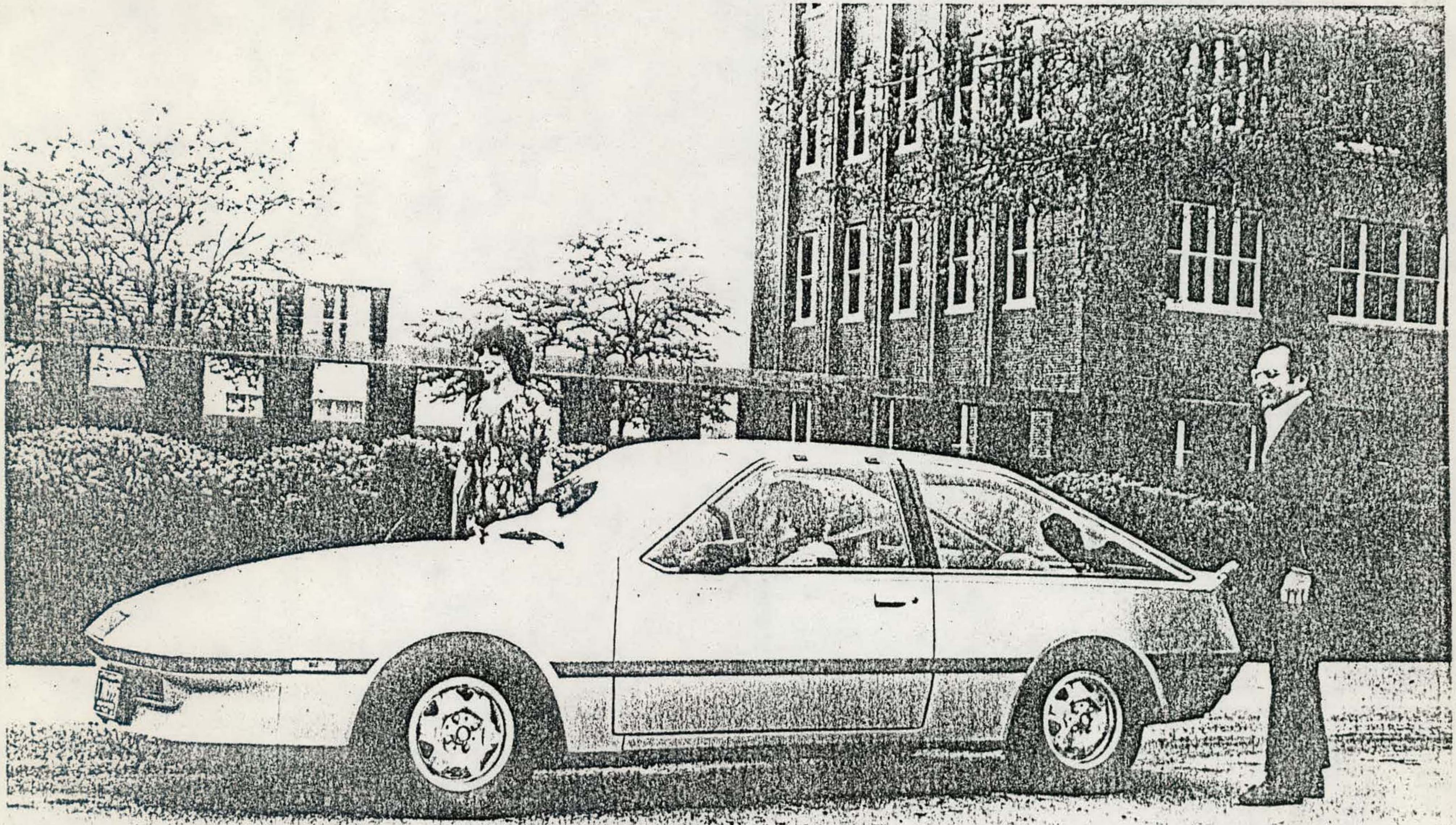
DISCLAIMER

I. Introduction

The genesis of the federal electric vehicle (EV) program is Public Law 94-413 (Electric and Hybrid Vehicle (EHV) Research, Development and Demonstration Act) passed by Congress in 1976 and later amended by P.L. 95-238 in 1978. Initial funding is $160 million for the first five years. As implemented by the Department of Energy (DOE) through its Transportation Program Office/EHV Division, the program contains three major elements: 1) research and development of batteries and propulsion systems to improve EV performance (creating a technology push), 2) demonstrations programs to display EV's capabilities (inducing a market pull), and 3) economic incentives to stimulate EV commercialization.

Argonne National Laboratory (ANL) is the Field Project Management Office for DOE's Near-Term Battery Research and Development Program. The ANL Near-Term Battery Project, initiated early in 1978 with current annual expenditures of about ten million dollars, is expected to produce batteries suitable for electric vehicle commercialization in 1986. DOE has established that a vehicle range of 100 miles in stop and go driving for a commuter car (50 miles for electric vans) is necessary for achieving the commercialization goal. State-of-the-art vehicles such as the DOE/ETV-1, designed and fabricated by General Electric/Chrysler (1) as shown in Figure 1, will more easily exceed this range when improved near-term batteries become available. Three near-term battery candidates receiving major developmental emphasis are improved lead-acid, nickel/iron and nickel/zinc systems. Thus, this paper discusses the programmatic development goals, the developers' approaches to achieve the goals, and the status of the three near-term battery technologies.



II. Department of Energy (DOE)/Argonne National Laboratory (ANL) Program

The strategy of the federal battery R&D program is to explore promising technical approaches which have a clear potential for meeting the DOE near-term battery applications requirements (2). The ANL program is industry-based using cost-sharing contracts with private battery developers. These industry-based efforts are supplemented by independent battery characterization testing at Argonne's National Battery Test Laboratory (NBTL) (3) and by additional supporting research efforts at Argonne, in universities, and at other research-oriented organizations. The central thrust of the battery R&D contracts is the design and fabrication of full-sized cells and modules which are suitable for the electric vehicle mission and can be commercialized by 1986. Cells/modules resulting from the contracts are placed under characterization testing by the respective contractors and in NBTL, used in prototype batteries for engineering and system testing simulations, and placed in engineering demonstrations in electric vehicles in order to obtain needed field operating data.

The DOE/ANL Near-Term Battery Project covers a wide range of technical approaches to battery development at present (4). Details of the present industry-based contracts are shown in Table I, where the total contract values given include the individual contractors' cost-sharing. During FY 1981, ANL will perform a selection of contractors within each system in order to focus resources more carefully onto the most promising technologies. Later, during FY 1982, system selection among lead-acid, nickel/iron and nickel/zinc systems will be made to choose the most suitable technologies for commercialization.

In order to provide focus to the R&D work, a set of development goals specific to each system were established in 1977 and were incorporated into the contract with each developer. These goals have proven to be useful as ultimate

TABLE I

DOE/ANL INDUSTRIAL CONTRACTORS FOR NEAR-TERM BATTERY R&D PROJECT

Battery	Contractors	Contract Period	Contract Value,[a] $
Lead-Acid	Eltra Corporation	04/78-05/81	2,576,969
	ESB Technology Co.	02/78-01/82	3,385,544
	Globe-Union, Inc.	03/78-04/81	3,042,783
Nickel/Iron	Eagle-Picher Ind., Inc.	03/78-02/81	2,074,725
	Westinghouse Electric Corporation	12/77-11/80	2,005,306
Nickel/Zinc	ESB Technology Co.	04/79-03/82	1,096,634
	Energy Research Corp.	03.78-02/81	3,105,764
	Gould Inc.	01/78-09/80	5,736,121
	Yardney Electric Corp.	07/77-05/79[b]	1,000,000

[a] Includes contractors' share

[b] Contract terminated by mutual agreement in May 1979

performance targets, but it has become increasingly necessary to form intermediate performance projections (5) for each system in order that battery technology progress can be more readily measured, and to allow needed system integration studies to be performed. The existing goals, shown in Table II, are currently being revised in order to more accurately reflect the recent DOE EV mission (100 miles urban range for a commuter car). The realignment of goals is likely to result in the lowering of targets for specific energy (to about 50-60 Wh/kg) and specific power (to about 100 W/kg) while maintaining maximum possible emphases on battery cost and lifetime.

III. Technical Approaches to Battery Development

A. Lead-Acid Approaches

In the lead-acid EV battery program, there are two separate, but concurrent, efforts, namely the improved state-of-the-art (ISOA) battery and the advanced lead-acid battery. The lead-acid research and development projects are conducted by ESB Technology Co. (Yardley, PA) (6), Globe-Union Inc. (Milwaukee, WI) (7), and Eltra Corporation (Plymouth Meeting, PA) (8). Each contractor is pursuing unique technical approaches.

ESB's approach to the ISOA program is based upon modifications of their commercially available EV-106 battery. Factorial experiments have been carried out to optimize the key design parameters (9). Four variables for the positive plate composition, two types of separator materials, two values for the electrolyte concentration and two forms of cell construction (outside positive and outside negative) were chosen. In order to evaluate the 32 different variable combinations, 96 three-cell modules were constructed and life-cycle tested.

Table II

ELECTRIC VEHICLE BATTERY DEVELOPMENT GOALS

	Lead-Acid		Nickel/Iron		Nickel/Zinc	
	1981	1984	1981	1984	1981	1984
Specific Energy[a] (Wh/kg)	42	55	54	70	64	85
Specific Power[b] (W/kg)	105	120	110	140	110	160
Cycle Life[c]	400	1000	300	2000	200	800
OEM Price[d] ($/KWh)	-	40	-	70	-	70

[a] At C/3 discharge rate

[b] 30 second average at 50% state-of-charge

[c] Cycled at 80% depth-of-discharge

[d] At a production level of 100,000 units (25KWh)/year

ESB has identified several combinations which exhibit energy densities greater than 40 Wh/kg which is the goal for the ISOA battery. However, the cycle lives of these modules are less than desired. For increasing cycle life of the battery, ESB started another series of factorial experiments by using tubular positive plates. This series of experiments consists of 96 3-cell modules and their cycle life appears to be good and the modules are still on testing.

For advanced batteries, ESB has adopted two approaches: one uses bipolar construction to increase the active material utilization while the second reduces grid weight by using plastic composite grids. For the bipolar construction, titanium biplate was used. ESB had allowed one year's time for testing the feasibility of the bipolar concept. During the period, they had made considerable progress in finding suitable means to construct the bipolar cell. However, their final analysis, considering factors such as substantially higher material cost, undetermined cycle life and low energy density (about 20 Wh/kg), has reached the conclusion that it would not be profitable to continue the bipolar effort. Alternatively, ESB's development of plastic composite grids looks promising. The negative grid weight has been reduced by 50% without compromising cycle life capability; negative plates incorporating plastic composite grids have achieved over 500 cycles without failure.

ESB has also subcontracted a computer modeling study of grid design to Battelle Memorial Institute, Columbus, Ohio. The study investigated voltage drop at the conduct lug and current distribution over the plate in a cell. It is believed that a more uniform current density distribution will result in better active material utilization and thereby yeild longer life for the battery. Lower voltage drops provide better energy and power densities when considered in conjunction with better active material utilization. Two grid designs have emerged from this study, i.e., an orthogonal and a radial concept. Battelle's conclusions are that, (1) cell voltage loss can be lowered by at least 50-80 mV and (2) the current density variability will be halved.

Globe-Union's approach has concentrated on the simultaneous optimization of cell design, material screening and manufacturing processes. Among the cell design optimization, such as size and number of plates, acid concentration etc., Globe's unique feature is a pump system attached to the module for intra-cellular electrolyte circulation. They believe that the circulation will increase and energy density as well as cycle life of the battery. During the period of development, Globe has identified low corrosion alloy for grid material and conditions of manufacturing process which give longer cycle life (10).

For the advanced battery, Globe relies on further optimization of design and inactive material weight reduction. A lead-plastic composite grid has been developed and a method for its manufacture has been established. In addition, a considerable amount of effort has been expended in expander research for the negative electrode. In the expander research, Globe has quantify two indices, "high rate index" and "cycle life index", to correlate the effect of lignosulfonates on the negative electrode. They use microelectrode for the study, which can produce many cycle life data in a short period of time. They have found that distinct molecular weight fractions of the lignosulfonate specifically influence the initial capacity and maintenance of capacity during cycling of the negative electrode. The data obtained from the microelectrode correlate well with that obtained from the full-size electrode in an actual battery (11).

Eltra's approach is based upon an expanded metal process (12) for the fabrication of both positive and negative grids. Pb-Ca-Sn alloy (0.08% Ca) is used as the base metal. Lead-calcium alloys have lower self-discharge rates and less grid corrosion than conventional antimonial alloys. In addition, calcium alloys have the advantage of low water loss and the absence of poisonous gasses such as stibine and arsine during charging. Eltra has optimized the grid thickness for both the positive and negative electrodes using 1.280 sp. gr. sulfuric acid as the electrolyte and experimenting with a number of separators such as PVC, rubber, microporous polyethylene and non-woven polypropylene. Eltra has installed a pilot-line facility for producing the expanded metal grids and for manufacturing EV and SLI batteries at the Prestolite Division in Toledo, Ohio. The pilot-line is operational at this time (13).

For the advanced battery, Eltra has investigated processing parameters that will lead to increased energy density and cycle life. A proprietary additive has been added to the electrolyte which reduces shedding of positive active material. The use of preformed tetrabasic lead sulfate in the positive plate is also expected to produce a longer cycle life battery (14).

B. Nickel/Iron Approaches

The nickel/iron research and development projects are conducted by Westinghouse (15) (Pittsburgh, PA) and at Eagle-Picher Industries (16) (Joplin, MO). In addition, Eagle-Picher has subcontracted specific iron electrode and separator work to the Swedish National Development Company. The two developers have common performance goals, but offer different approaches to the technical problems.

Westinghouse is emphasizing development of a battery which has adequate performance and a low initial cost (17). However, this development will not compromise the promise of long cycle lives inherent in nickel/iron battery electrochemistry. Westinghouse has sintered steel wool current collectors for both the positive nickel and negative iron electrodes. The positive electrode steel wool is nickel plated in order to avoid undesirable irreversible side reactions within the cell. The nickel hydroxide active material is impregnated into the positive electrode by either of two processes which are under parallel development -- electrochemical or pasted. Electrochemical impregnation, also called electro-precipitation, is at a more refined state of development at this time. During the current project, Westinghouse has improved the performance of the electro-chemically prepared positives by 10% and has reduced the manufacturing costs as well. Since the nickel positive is generally the performance and cost limiting component in nickel/iron batteries at normal temperatures, these improvements translate directly into product improvements. However, the pasted positive electrode process offers even potentially lower production costs. Iron negative electrodes are prepared at Westinghouse by pressing an iron oxide paste into the prepared steel wool substrate followed by sintering at a higher temperature in a reducing atmosphere.

In addition, Westinghouse has designed an active gas and electrolyte management system (18) for their battery that controls and minimizes the safety hazard associated with hydrogen gas generated during charging. This system, which features circulating electrolyte, can be either installed with the battery on-board the vehicle, or made a part of the battery charger, depending on the particular characteristics and mission of the vehicle. On-board electrolyte circulation offers the potential for active battery cooling during discharge, if an associated heat exchanger for electrolyte cooling is also installed.

The Eaglė-Picher nickel/iron battery features a high performance approach using a proprietary nickel positive electrode and iron negative electrodes from the Swedish National Development Company (19). The Eaglė-Picher positive electrode is electrochemically impregnated using a powder metallurgically prepared porous sintered nickel plaque. Conventional plaque fabrication relies upon a continuous wet slurry method that is limited to plaques which are less than 1 mm thick. But, the particular characteristics of the electric vehicle application demand electrodes which are 2-3 times this thickness. Eagle-Picher has concentrated on developing electrodes which are this thick, can be economically produced, and have uniform, high performance. The Swedish National iron electrode consists of a sintered iron plaque. This plaque is manufactured using iron powder, and active material impregnation can be accomplished simultaneously with plaque preparation. Iron electrodes developed during this project have achieved 90% of the program goal of 1 Ah/cc at room temperature. Swedish National has defined the iron negative electrode as being the key element needing development to improve the low temperature performance of the nickel/iron battery. Also, trace elements in the iron electrode have been identified which significantly affect performance. Historically, a trace amount of sulfide ion has been found to have beneficial effects. Swedish National has also defined a ribbed, sintered PVC separator which is suitable for nickel/iron batteries. The Eagle-Picher nickel/iron system has a noticeably improved energy efficiency -- 67% vs. a more typical 50% -- in recent tests. This improvement is attributed to the iron electrode being used.

C. Nickel/Zinc Approaches

The four contractors who have performed research and development on Ni/Zn batteries are Gould (Rolling Meadows, IL) (20), Energy Research Corp. (Danbury, CT) (21), Yardney Electric Corp. (Pawcatuck, CT) (22), and ESB Technology Co. (Yardley, PA). All contractors have attempted to reduce battery life-cycle costs (i.e., the amortized battery cost plus cost of operation during lifetime) while maintaining or improving performance, but each has taken different approaches to achieve that end.

Gould (23) is developing improved separator systems to extend cycle life. Both microporous as well as membrane-type separators have been investigated. Microporous separators, such as Celgard (polypropylene) and inorganic/organic composites, have been de-emphasized because they are susceptible to accumulation of zinc within the pores of the separator, leading to cell failure. Gould has developed membrane-type separators based upon cross-linked polymeric films, which are zinc-free, stable in KOH, have low ionic resistivity, and are capable of low-cost production. In addition, a new synthetic wicker material has been utilized as an interseparator. A number of proprietary additives, both to the zinc electrode and to the electrolyte, have also been investigated for extending cycle life. The role of the additives is to alter the characteristics of zinc dissolution and deposition in such a way as to suppress dendrite formation and shape change in the zinc electrode. Small (5 Ah) cells with such additives have operated for 250 deep cycles, whereas control cells containing no additives only operated for 60 cycles. In the area of thermal management, Gould has developed a model (24) that accurately portrays heat generation and rejection rates during actual battery operation. This had led to the redesign of cells from a capacity of 400 to 225 Ah (thinner cell) and a redesign of modules to include cooling channels between cells in order to provide better thermal control. Gould believes that the development of advanced fabrication techniques for sintered nickel electrodes, coupled with their superior performance, will reduce the life-cycle costs sufficiently to make the sintered electrode as economically attractive as the non-sintered plastic-bonded nickel electrode.

Energy Research Corporation (ERC) is emphasizing the development of a Ni/Zn battery with a low initial cost (25). Efforts are focused on the nickel electrode, which is the most expensive component in the battery. The technical approach is based upon the development of a low-cost, plastic-bonded electrode fabricated from chemically precipitated nickel hydroxide. This electrode contains about 30% graphite as a conductive diluent in place of the conventional sintered nickel-powder plaque. The cost of the plastic-bonded electrode is projected to be half that of a comparable sintered nickel electrode. To achieve longer lifetimes in their Ni/Zn cells, ERC is investigating cast-film separators (26). Two separator materials, cross-linked polyvinyl alcohol and a thermoplastic-based composite, have been developed with low ionic resistivities and are currently undergoing life-cycle evaluation in 20 Ah test cells. An additional approach to achieve the same objective is through additives to the zinc electrode to reduce shape change. The development of sealed cells is also being pursued by ERC as a means to reduce or eliminate maintenance (addition of water) and possibly to extend life. To keep hydrogen and oxygen pressures low in sealed cells, auxiliary electrodes or pocket catalysts are being employed to promote recombination of these two gases. Early results are favorable, but much additional work will be required before cell capacities, which have been found to be limited during charge by gas pressure build-up, are equal to those of standard vented cells.

ESB is pursuing a unique cell design approach based upon vibrating zinc electrodes (27, 28). When the zinc electrode is vibrated during charging, the lifetime limiting problems of zinc dendrite formation and electrode shape change are surmounted. Since vibration is required only during charging, most of the added weight required for vibration could be incorporated into an off-vehicle charger. The vibrating zinc electrode also result in high utilization of negative active material. Consequently, much less zinc is required. Thus, the ratio of negative-to-positive theoretical capacity is only 1.2 for the vibrating anode cell, compared to a ratio of 2 to 4 for conventional Ni/Zn cells.

The emphasis of the present work at ESB is to increase the gravimetric and volumetric specific energy of the system, while retaining the long cycle-life capability. To this end, the following design changes are being examined in Ni/Zn cells: higher specific capacity nickel electrodes, thinner zinc electrodes, and smaller inter-electrode spacing. The nickel electrode improvements consist of replacing the pocket-type electrode (75-90 Ah/kg) used in the past by a suitable high capacity electrode (110-140 Ah/kg). Several types are being evaluated, including electrochemically impregnated sintered nickel (Matsushita), pasted metal wool (D.A.U.G. Mercedes), and layered nickel foil (INCO's CMG electrode). The plastic-boneded nickel electrode of ESB was found to have excessive swelling in the unrestrained structure inherent in the vibrating anode cell and was therefore removed from consideration. A reduction in thickness of the zinc electrode at constant capacity per plate has been made possible as a result of special charging techniques that create much denser zinc deposits on the negative substrate without the loss of high-rate discharge capability. In addition, the denser zinc deposits are more adherent; as a result, slumping of active material from the vibrating electrode has been largely eliminated. Studies are underway to evaluate the effect of inter-electrode spacing and to determine its optimal value. A reduction in spacing from the 2.5 mm used in previous cells to 1.5 mm if feasible, would result in a 20% improvement in volumetric energy, concomitant with a yet to be determined increase in specific energy. Other studies are aimed at selecting a negative electrode substrate material that will reduce the present self-discharge rate of 8% loss in capacity on a five-day charged stand.

The Ni/Zn battery R&D contract with Yardney (22) was terminated by mutual agreement on May 31, 1979 at the end of Phase I of their development program because Yardney decided the business risk was too great to continue further cost-sharing with DOE. The Phase I program had focused on reducing the initial battery cost and improving component lifetime. Early in the program, a failure-modes analysis established that the negative electrode was responsible for capacity degradation during cycling. The use of additives and binder in the zinc electrode, improvements in the separator system, and an alternative charging technique were employed to mitigate this problem. Subsequent attempts to increase cell life emphasized combining the strengths of both diffusive and microporous-type separator materials. Initial efforts to reduce cost dealt primarily with the development of a plastic-bonded nickel electrode. However, the poor performance (reduced capacity at high discharge rates and low volumetric energy density per plate) led to the abandonment of this approach in favor of the sintered electrode. The cost of the sintered electrode was reduced by fabricating a thicker, more porous plaque as well as streamlining the manufacturing process. Collectively, these steps reduced the amount of nickel, labor, and processing required for this electrode (29).

IV. Technical Status

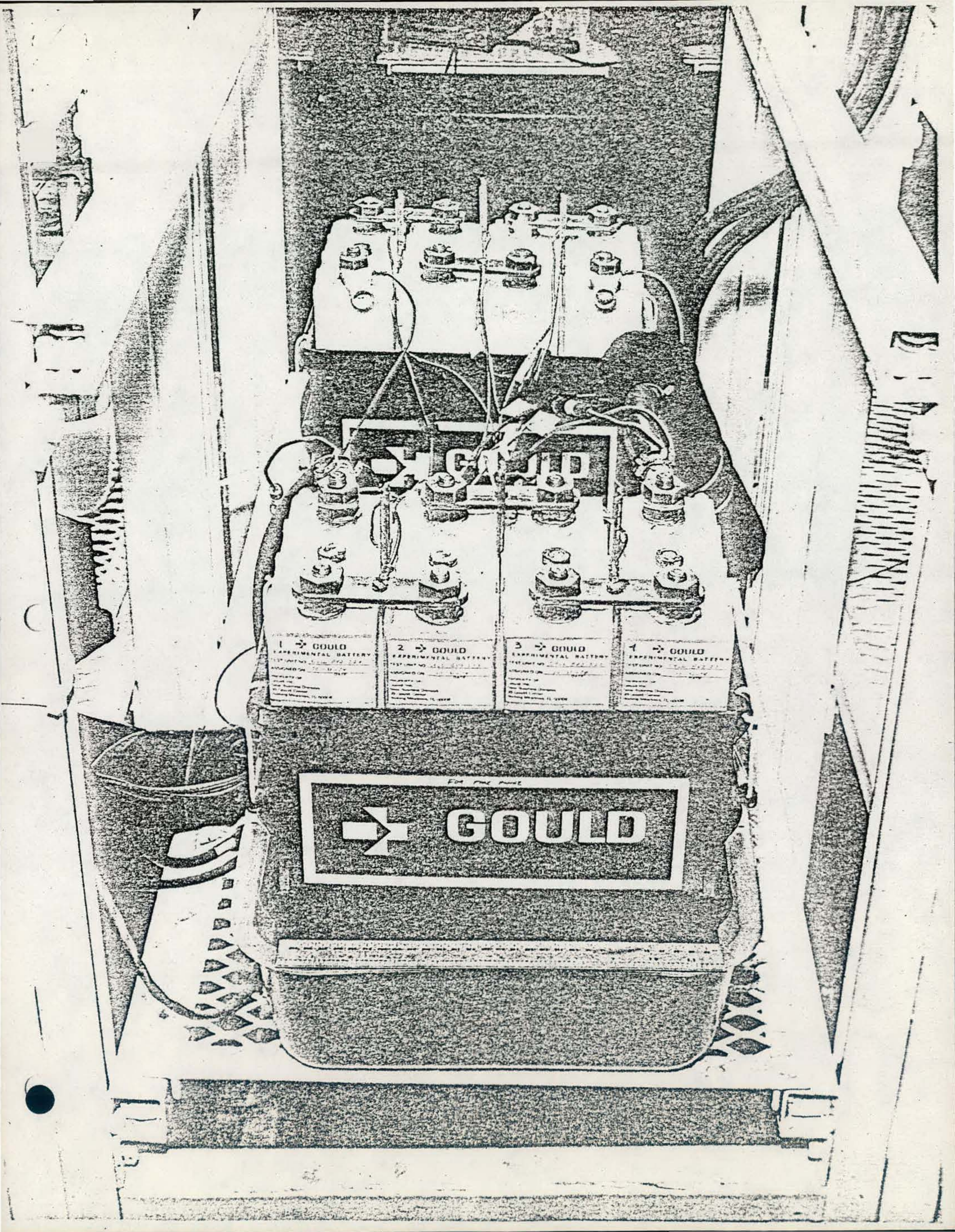
The lead-acid, nickel/iron and nickel/zinc batteries under development by ANL contractors are described in Table III and shown in Figures 2 through 9. The present characteristics shown reflect the status of the technology in 1979, while the future numbers shown represent expected results in 1984. As such, the present technology is an interim baseline design, which is being built and tested in order to resolve outstanding technical problems and to demonstrate system capabilities. Since many designs are not, and will not be, direct physical replacements for the baseline EV-106 lead-acid battery [also shown in Table III for reference], careful vehicle integration will be needed to ensure achievement of the performance benefits offered by these batteries.

TABLE III

CHARACTERISTICS OF MODULES UNDER DEVELOPMENT IN THE NEAR-TERM ELECTRIC VEHICLE BATTERY PROJECT

Battery Type and Manufacturer		Weight (kg)	Dimensions LxWxH[1] (cm)	No. of Cells Per Module	Module Voltage (volts)	Energy (Wh)	C/3 Capacity (amp-hours)
Baseline Lead-Acid							
ESB EV-106		29.6	26.2 x 18.3 x 28.5	3	6.0	892	150
Improved Lead-Acid							
ESB		28.4	26.2 x 18.0 x 28.6	3	6.0	1047	180
Eltra		27.6	26.0 x 18.0 x 27.4	3	6.0	1062	186
Globe-Union		72.6	33.0 x 38.1 x 29.5	6	12.0	2928	249
Nickel/Iron							
Westinghouse	- Present	27.4	23.5 x 17.8 x 29.9	5	6.0	1330	220
	Future	25.0	26.1 x 18.1 x 28.6	5	6.0	1460	240
EPI	- Present	37.5	35.6 x 18.4 x 28.6	5	6.0	1750	280
	Future	25.0	26.1 x 18.1 x 28.6	5	6.0	1460	240
Nickel/Zinc							
ERC	- Present	34.9	29.8 x 18.2 x 33.5	4	6.4	1600	250
	Future	27.0	29.8 x 17.8 x 33.0	4	6.4	1648	250
Gould	- Present	42.0	33.0 x 17.8 x 40.0	4	6.4	2560	400
	Future	30.0	27.3 x 17.8 x 39.2	5	8.0	1800	225
ESB	- Present	28.8	32.0 x 21.0 x 28.3	4	6.4	1440	225
	Future	27.0	28.0 x 17.3 x 26.1	4	6.4	1600	250
Yardney		28.2	25.6 x 17.8 x 28.4	4	6.4	1600	250

[1] Includes Terminals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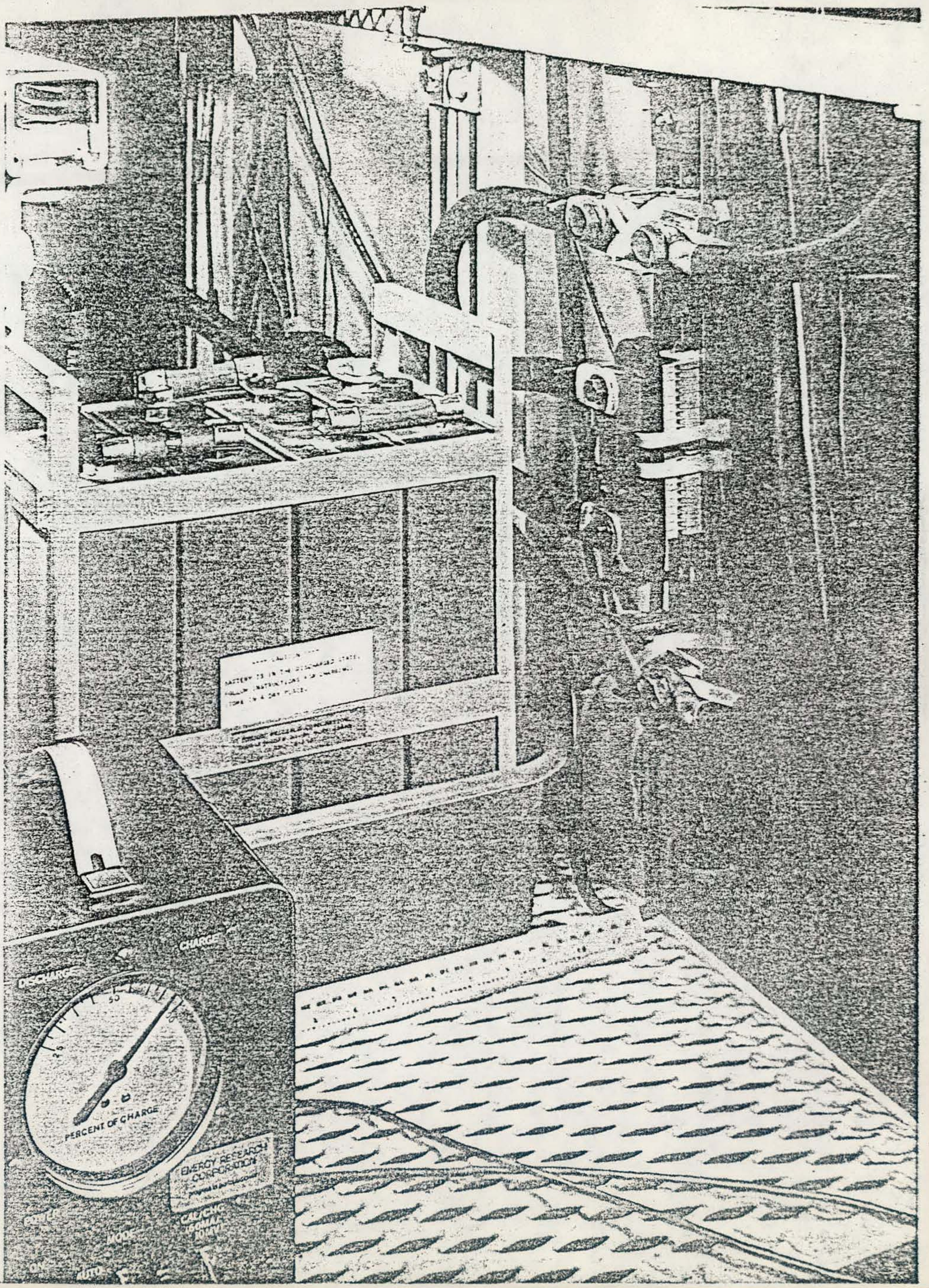
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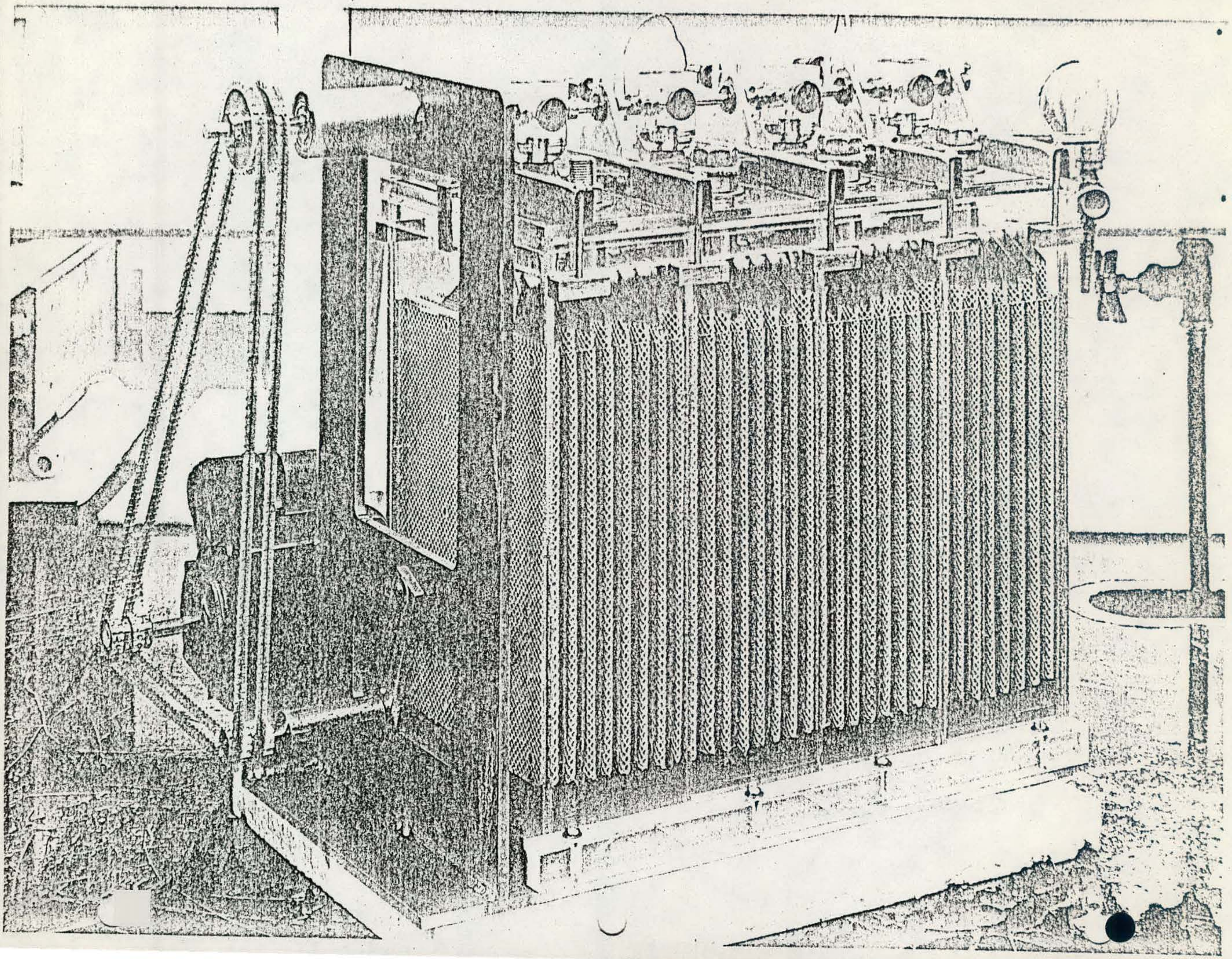

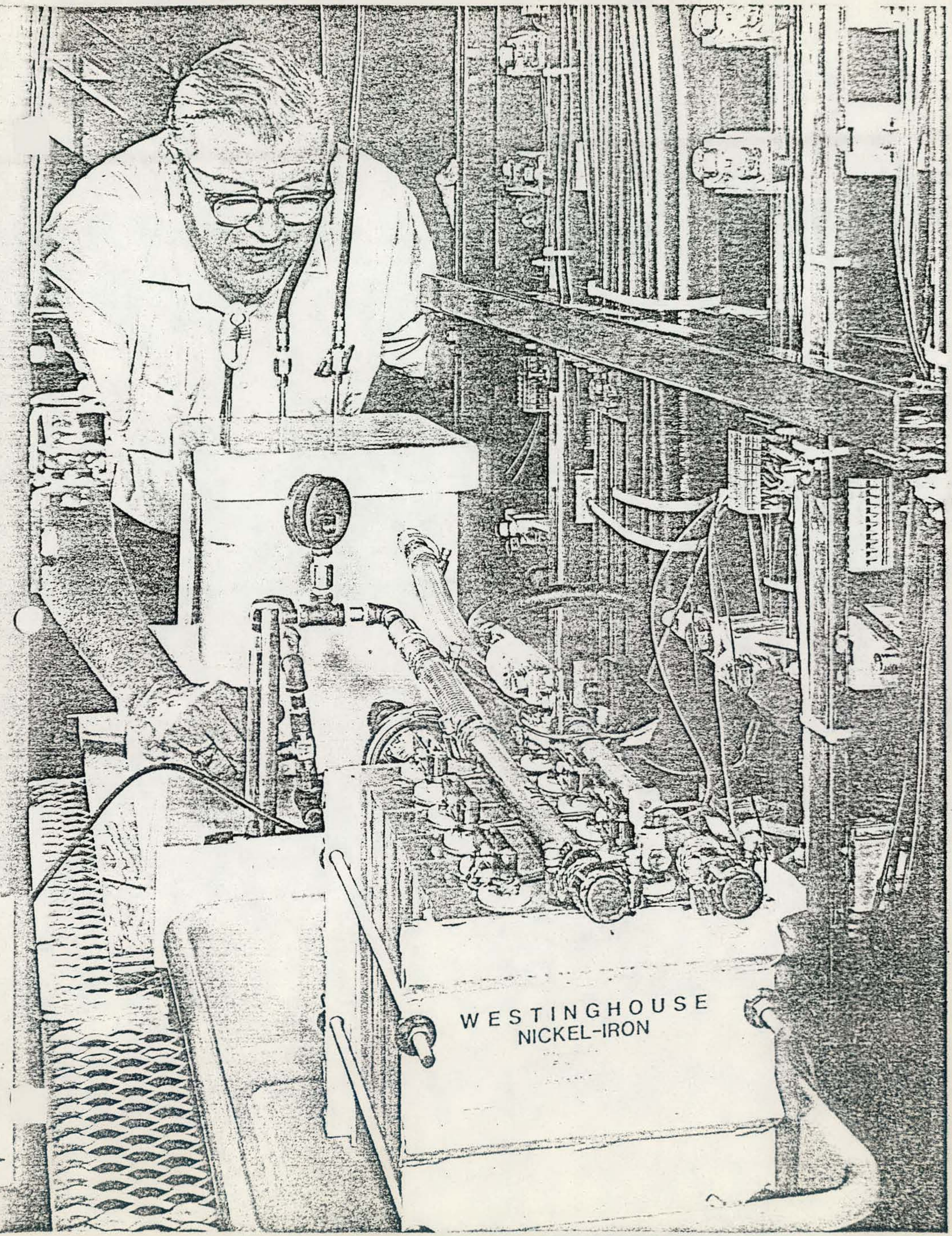
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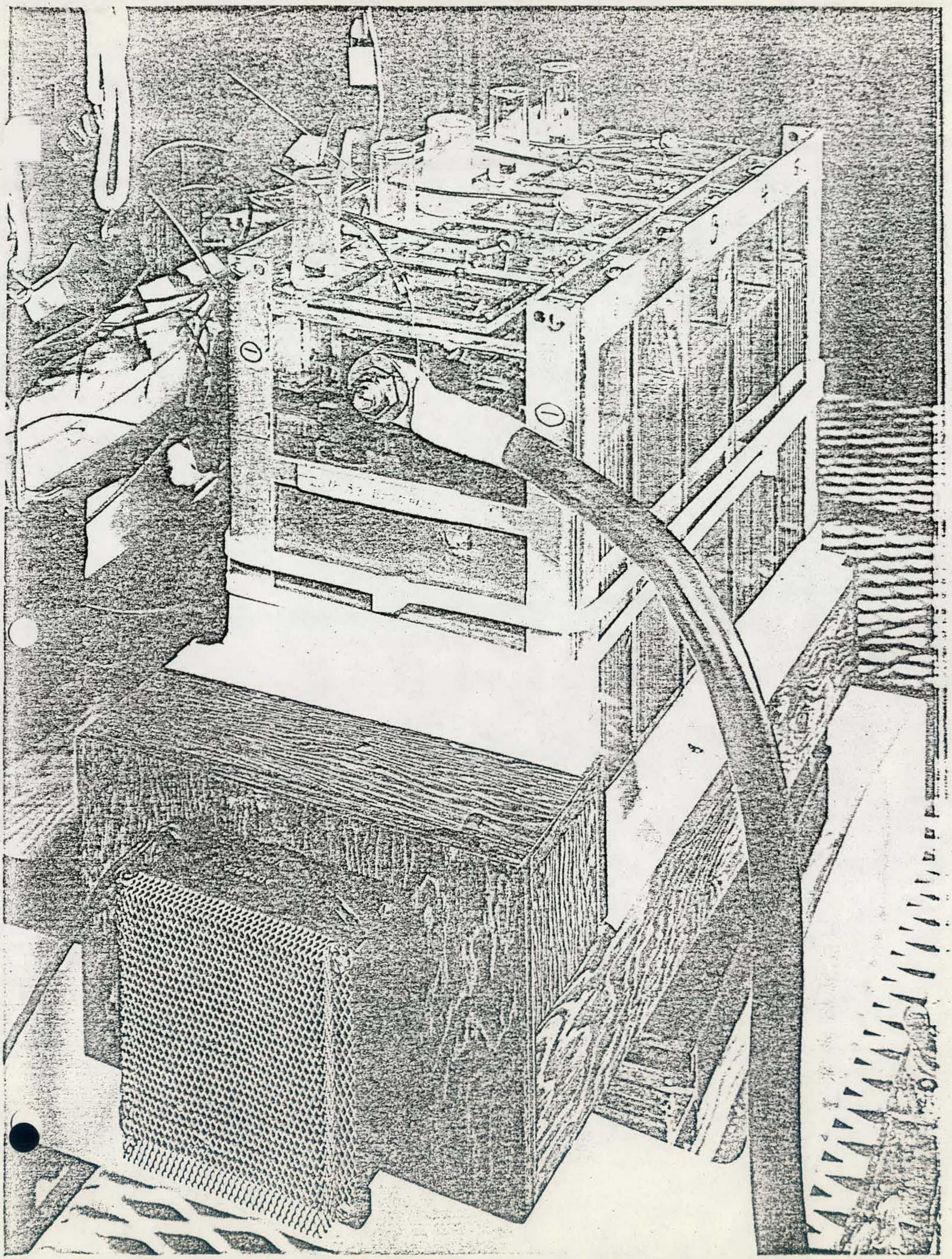

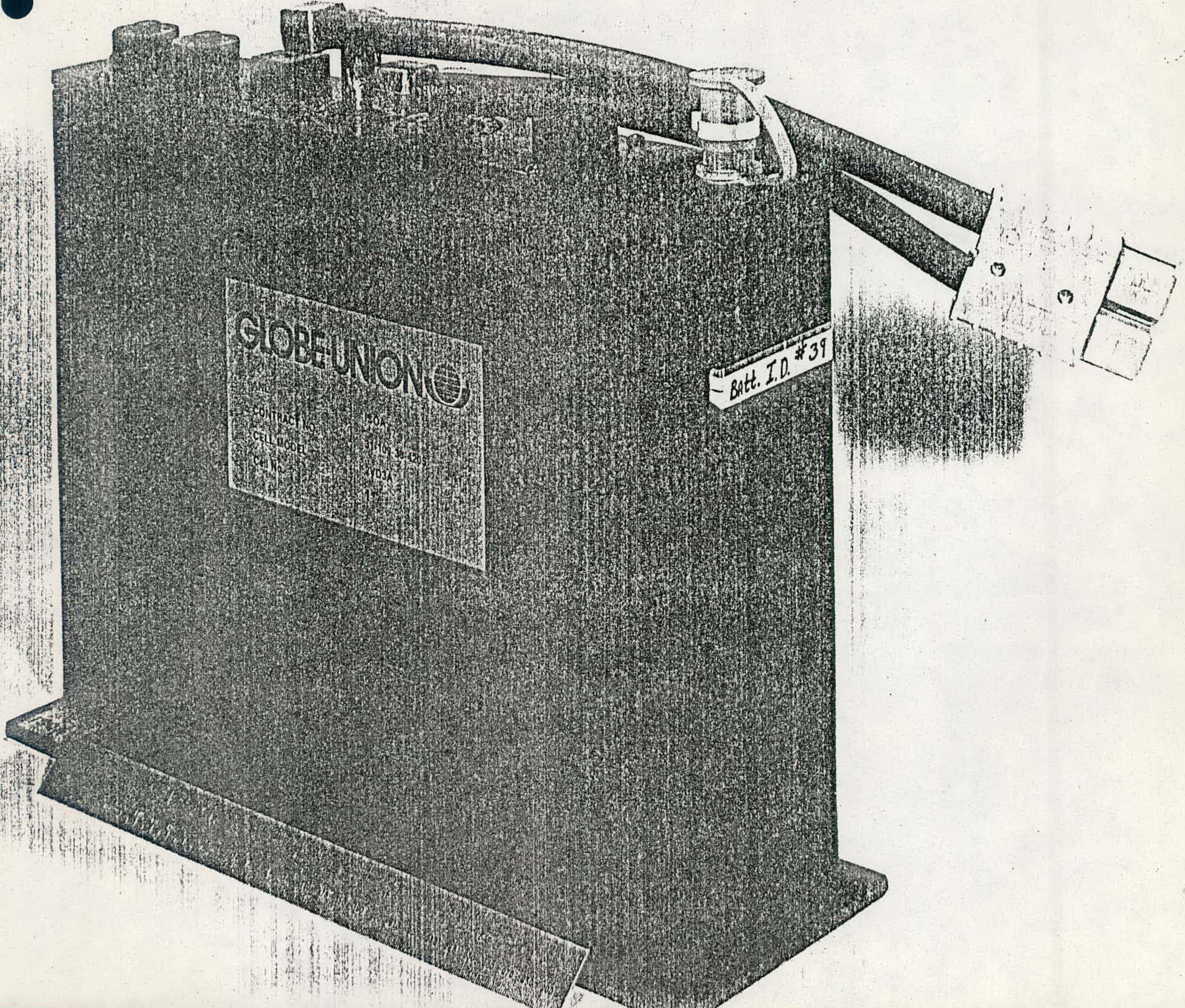
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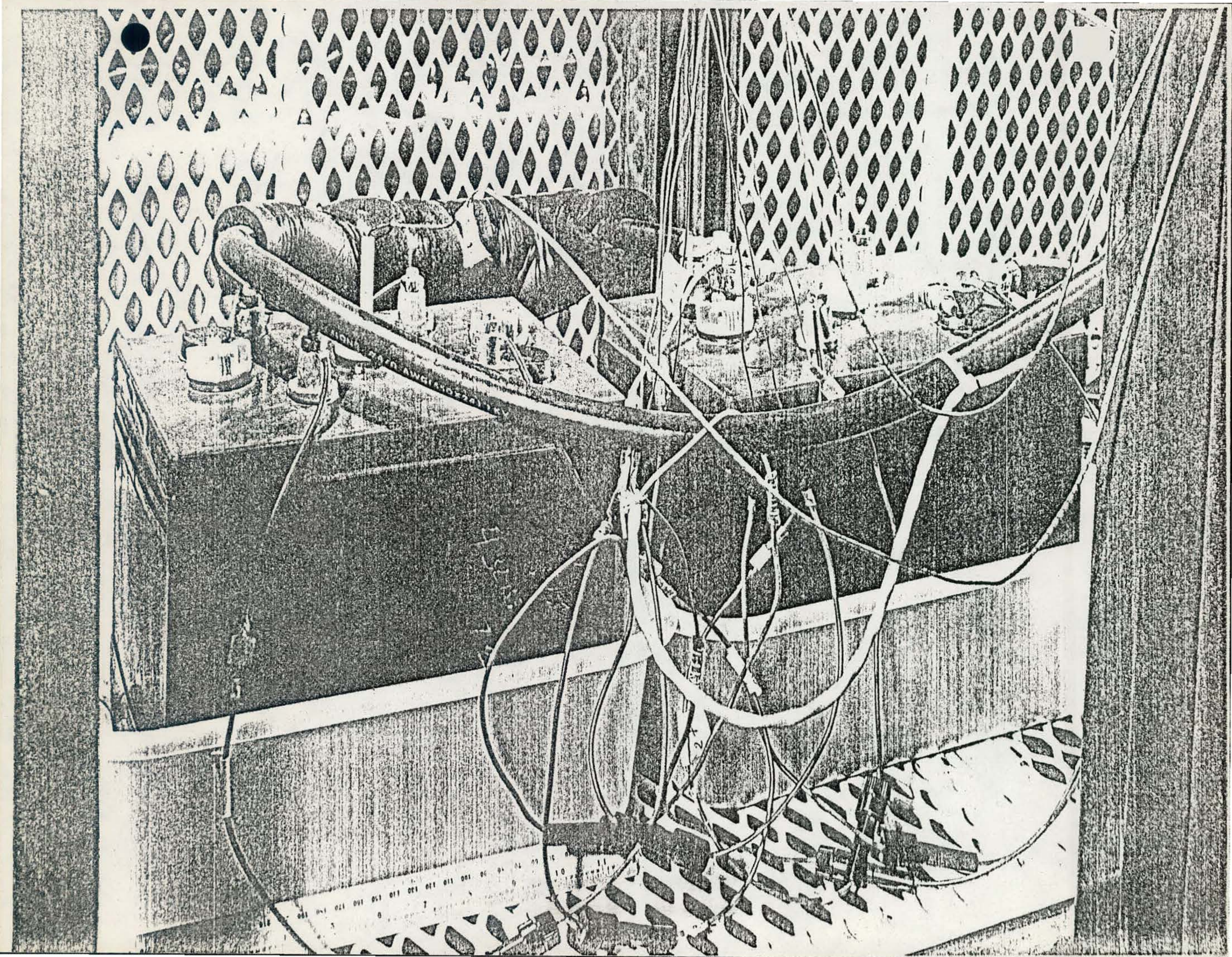

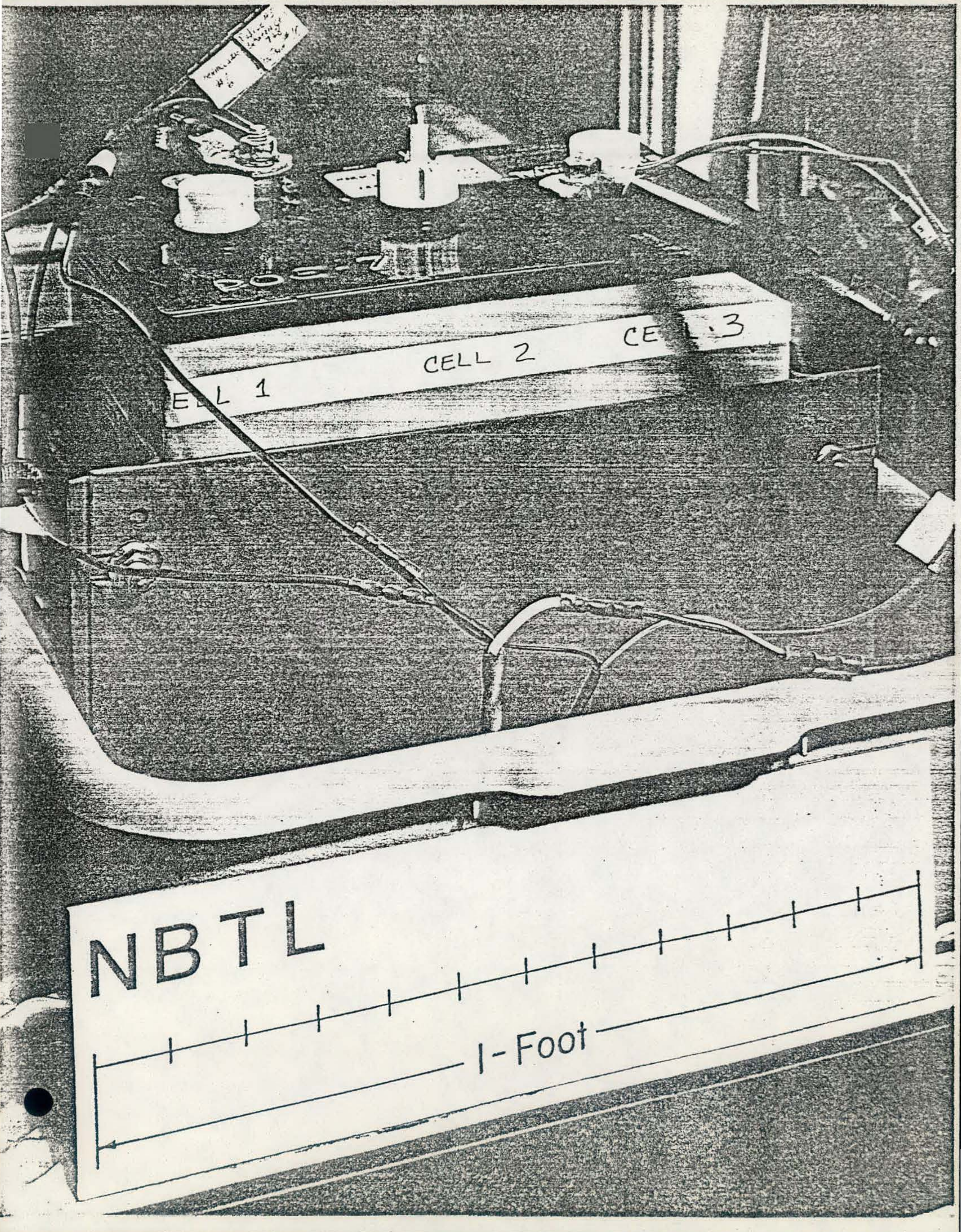
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Table IV shows one approach which can be used to assemble the modules shown in Table III into an electric vehicle battery pack. Table IV is based on a constant mass replacement of 18 EV-106 lead-acid batteries by an approximately equivalent weight of improved batteries. In general, the table indicates that retrofit of these batteries into an existing electric vehicle design which is largely based on the EV-106 is not always possible if the same system voltage is required. Other methods of assembling modules into vehicle battery packs, are, of course, possible. For example, one can perform a similar substitution as was done above, but instead using a constant volume. A different set of battery mass, energy voltage, and volume results. Such design analysis reflects the importance of total vehicle system integration which directly impacts on the battery design. The module characteristics (shown in Table III) were derived from battery optimization studies for electric vehicle applications and, as such, they serve as the baseline designs from which specific battery designs will be conducted for specific vehicle requirements.

The present technical status of EV battery technology is reflected in test results obtained to date at the inidividual contractor laboratories and by verificational testing conducted at the National Battery Test Laboratory (NBTL). Table V summarizes those results; both contractor and NBTL results have been included. Differences between the two arise from 1) differences in test procedures, such as the number of cycles per day, recharging procedures, and the number of characterization cycles prior to life cycle testing, 2) the fact that contractor data are for cells, whereas NBTL testing is conducted on multi-cell modules, and 3) contractor tests are the latest results based upon the best of current design variations, whereas NBTL testing is conducted upon those modules which have demonstrated the promise of adequate performance at the contractor's site in the prior 3-6 months.

TABLE IV

CHARACTERISTICS OF A TOTAL VEHICLE BATTERY SET HAVING APPROXIMATELY SAME WEIGHT AS 18 ESB EV-106 MODULES

Battery Type and Manufacturer		No. Of Modules Per Battery Set	Battery Set Weight[a] (kg)	Energy Per Battery Set (WH)	Battery Set Voltage[b] (Volt)	Accessories	Comments
Baseline Lead-Acid							
ESB EV-106		18	532.8	16,056	108.0	None	Cooling & Ventilation air needed
Improved Lead-Acid							
ESB		19	539.6	19,893	114.0	"	"
Eltra		19	524.4	20,178	114.0	"	"
Globe-Union		7	508.2	20,496	84.0	"	"
Nickel/Iron							
Westinghouse	- Present	19	540.6	25,270	114.0	Electrolyte & reservoir pump = 20kg, 40 liter	Cooled by circulating electrolyte
	Future	21	545.0	29,200	126.0	"	"
EPI	- Present	14	525.0	24,500	84.0	None	Cooling and ventilation air needed
	Future	21	525.0	30,660	126.0	"	"
Nickel/Zinc							
ERC	- Present	15	523.5	24,000	96.0	"	"
	Future	20	540.0	32,960	128.0	"	"
Gould	- Present	13	546.0	33,280	83.2	"	"
	Future	18	540.0	32,400	144.0	"	"
ESB	- Present	18	518.4	25,920	115.2	"	"
	Future	20	540.0	32,000	128.0	"	"
Yardney		19	535.8	30,400	121.6	"	"

a) Not including vehicle structure to support and hold down modules, but does include any battery accessory weight.

b) For all modules electrically in series

TABLE V

TEST RESULTS SUMMARY

	Energy Density[a] (Wh/kg)		Specific Power[b] (W/kg)		Cycle Life[c]		Urban Range[d] (miles)	
	NBTL	Contractor	NBTL	Contractor	NBTL	Contractor	w/R.B.	w/o R.B.
Baseline Lead-Acid								
ESB EV-106	30	-	97	-	(250)[f]	-	60	46
Improved Lead-Acid								
Globe-Union	41.4	42.5	-	118	203	350	79	62
ESB	35.6	40.4	-	-	116	120	74	63
Eltra	37.0	39.2	-	114	52	125	-	-
Nickel/Iron								
Westinghouse	48	58	98	100	>300[e]	300	96	78
Eagle-Picher	47	52	103	100	>160[e]	300	-	-
NIFE Jungner AB	40	45	-	50	-	(1000)[f]	-	-
Nickel/Zinc								
Gould	67	71	133	130	120	210	140	114
Energy Research	46	52	-	-	76	100	-	-
ESB	-	42	-	100	-	(1000)[f]	-	-
Eagle-Picher	50	-	-	-	61	-	97	80
Yardney	62	66	-	-	29	125	91	77

a) At C/3 rate
b) 30-second average at 50% state-of-charge
c) Cycled to 80% depth of discharge; life to 75% of rated energy
d) Simulated test at NBTL for GE/Chrysler car (ETV-1) on SAE J227a/D cycle; with and without regenerative braking (R.B.), see Ref. (30).
e) Test continuing
f) Estimated

At NBTL, three types of tests are conducted. First, performance characterization determines the specific energy of a module and its peak power capability. Secondly, simplified driving profiles are imposed to simulate the requirements which would be demanded of the battery in an actual vehicle application. And finally, life cycle testing is conducted at 80% depth of discharge until the battery fails to deliver 75% of its rated capacity. These results are presented in Table V. The volumetric energy density of each system can be estimated directly from the gravimetric energy density, since the density of each system is approximately 2 kg/l (excepting the ESB vibrating electrode cell, whose density is yet to be established, but is expected to be somewhat less).

A. Lead-Acid Status

In the past, available lead-acid propulsion batteries suitable for EV application were mainly limited to golf-cart type batteries. These batteries have low specific energy, 25 to 30 Wh/kg, and low cycle life, estimated to range from 125 to 250 cycles. Since the initiation of the near-term EV battery project, all three industrial contractors for lead-acid batteries (ESB, Globe-Union, and Eltra) have developed improved state-of-the-art (ISOA) cells and modules which have exceeded the ISOA energy density goal of 40 Wh/kg. However, in each case, the cycle life has been less than desired, ranging from less than 105 to 350 cycles depending upon the contractor.

During 1979, ESB conducted a comprehensive factorial experiment, with 96 lead-acid modules of flat-plate design. In the course of this experiment, modules attained specific energies of up to 40.7 Wh/kg at the 3-hour discharge rate. Two 3-cell ISOA modules tested at NBTL operated for 116 and 105 cycles before the capacity declined below 75% of the manufacturer's rated capacity. Research on advanced batteries at ESB has compared the performance of three types of cells using flat-plate, tubular-plate, and bipolar electrodes. Of the three types, cells constructed with flat plates showed the best overall performance, particularly with respect to discharge voltage and cell capacity; cells with tubular-plate (37.7 Wh/kg, life testing in progress) and bipolar electrode construction (about 20 Wh/kg) have not achieved specific energy as high as that obtained by the flat-plate design. Accordingly, ESB has suspended further development work on the tubular and bipolar designs for the advanced battery in preference to the flat-plate design.

During FY 1979, Globe-Union delivered five 250 Ah cells to NBTL for testing. Three cells were put through characterization testing and demonstrated energy densities of 40.5-41.4 Wh/kg. The remaining two cells were life cycle tested and delivered 203 and 183 cycles before the capacity declined below 75% of the rated capacity. Thirty-second-average peak power at 50% state-of-charge was 118 W/kg for these cells. Predicted electric vehicle range for a battery of this design, based upon NBTL simulated driving tests (30), is 79 miles with regenerative braking and 62 miles without regenerative braking.

Eltra delivered three 3-cell modules to ANL in 1979. Maximum manifested specific energy in NBTL tests was 37 Wh/kg. The same type of cells tested at Eltra operated for only 125 cycles. For the advanced design, Eltra is experimenting with different formulations of the positive active material to improve cycle life. One of these formulations, which incorporates tetrabasic lead sulfate, has resulted in an increase of the cycle life from 125 to 183 cycles.

B. Nickel/Iron Status

Nickel/iron contractors delivered multicell modules to the NBTL during 1979. The demonstrated specific energy was 48 Wh/kg and 47 Wh/kg for the Westinghouse and Eagle-Picher modules respectively, with 30-second peak power densities of about 100 W/kg at 50% state-of-charge for both. In simulated driving profile tests, the Westinghouse module exhibited a predicted urban range of 96 miles with regenerative braking (30) and 78 miles without regenerative braking. The Eagle-Picher Ni/Fe module reached its specified temperature limit during this test, so comparable data are not avaiable.

Much was learned while fabricating and testing these first Ni/Fe modules that clearly indicates that 60 Wh/kg can be achieved prior to 1982. In fact, specific energies of 58 Wh/kg have already been demonstrated by cells tested in the contractors' laboratories. These latest full-sized cells contain improved electrodes which were not used in the delivered design of 1979.

The cycle life testing of the Ni/Fe modules is being continued. From full-sized cell tests at contractor laboratories, the present cycle life capability of the Ni/Fe modules is estaimted to be greater than 300 deep discharge cycles. Over 300 and 160 cycles have already been verified at the NBTL for the Westinghouse and Eagle-Picher modules, respectively.

The energy efficiency of the Westinghouse module has been 50%, whereas the contract goal is 60%. Eagle-Picher and their subcontractor (Swedish National Development Co.) have made notable progress in increasing the energy efficiency of this system to 67%. Further improvements are anticipated as battery charging techniques are refined and cell designs are optimized to minimize internal resistance.

C. Nickel/Zinc Status

The high performance approach adopted by Gould has resulted in Ni/Zn modules which have displayed a verified energy density in excess of 67 Wh/kg (C/3 rate) and a peak power at 50% state of charge of 133 W/kg (30 sec. average). The demonstrated cycle life was 120 cycles (to 80-100% depth of discharge) at NBTL, but recent cell tests at Gould have shown an increase in lifetime to 210 deep cycles. Simulated driving profile tests based on the requirements of the ETV-1 vehicle predict a vehicle urban range of 140 miles with the aid of regenerative braking (30) and 114 miles without regenerative braking. The turnaround energy efficiency is 77%, based upon a coulombic efficiency of 91% (110% recharge factor).

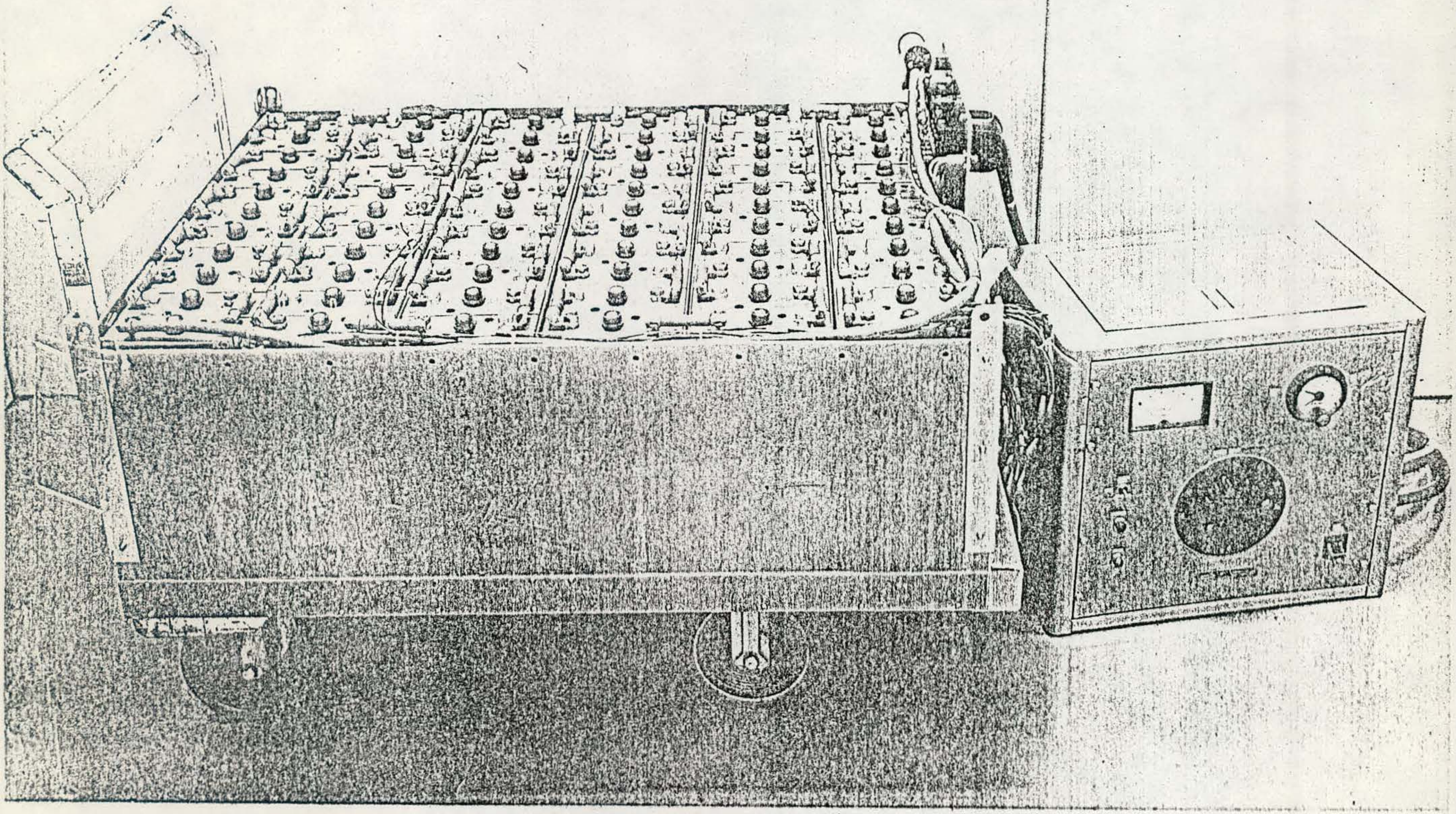
The low-cost approach adopted by ERC has yielded modules with understandably lower performance -- 46 Wh/kg at NBTL. Cycle life has also been limited, in full-size modules, to 76 cycles or less. While the low cost potential of the plastic-bonded nickel electrode has been retained, its performance has been steadily improved. In 20 A-hr Ni/Cd test cells, ERC demonstrated a lifetime of over 1000 cycles and a positive active-material utilization of 80% for their plastic-bonded nickel electrode. Early tests with full-size electrodes indicated poor utilization (55%) of the positive active material, but this problem was overcome by increasing the electrode porosity. Full-size cells (rated at 250 Ah), which incorporated nickel electrodes having increased porosity, have exhibited capacities of 239-266 Ah and nickel utilizations of 76-84%.

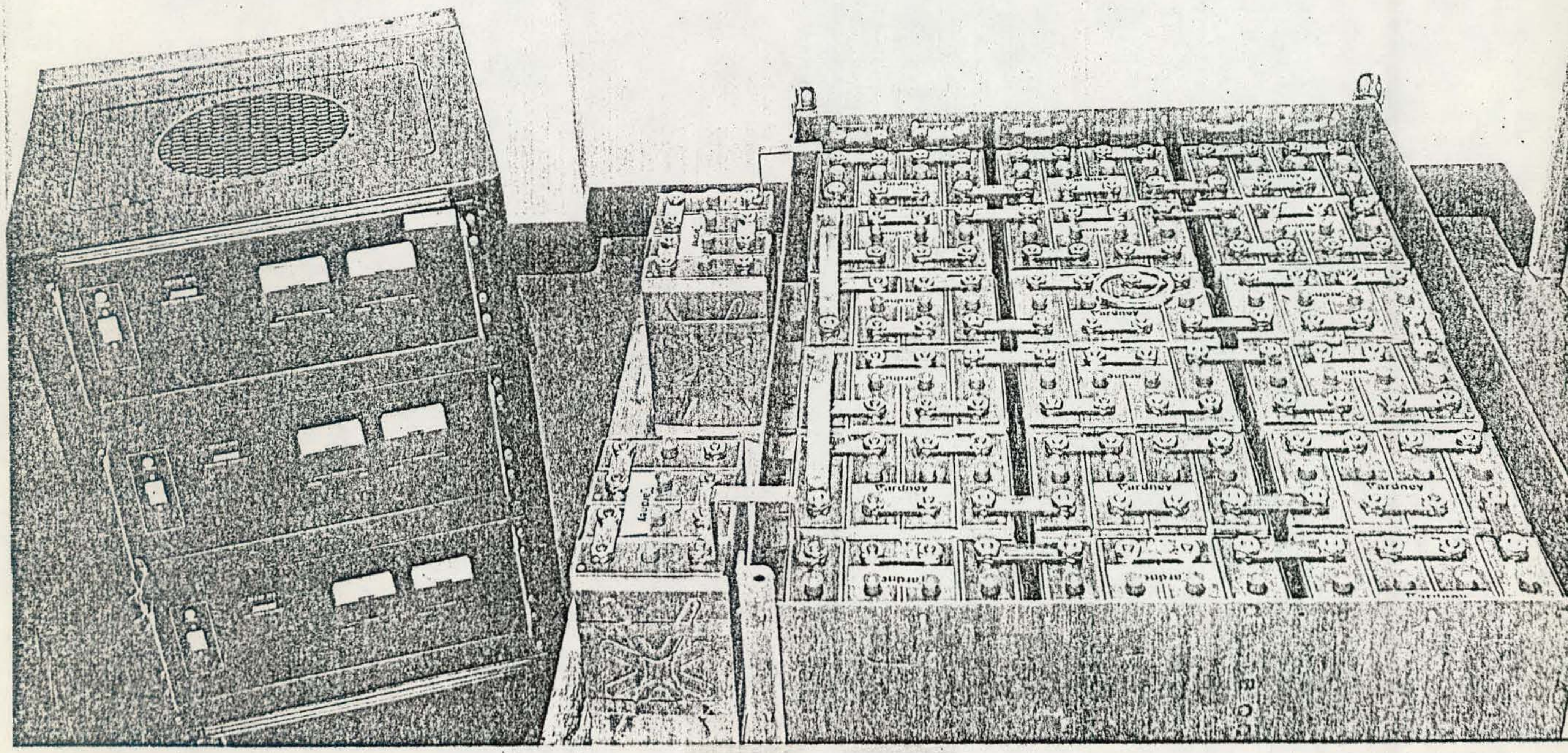
ESB's developmental work is based upon prior work at their Swedish Tudor subsidiary, in which the long lifetime capability (over 1000 cycles) of the Ni/Zn system with the vibrating zinc electrode had been demonstrated in a six-cell, 145 Ah module (27). However, the specific energy of that module was limited to 40 Wh/kg at the 3-hr. rate. ESB has designed a scaled-up 300 Ah cell as a baseline and a four-cell module of this design has been construcuted and delivered to NBTL. This prototype has an energy density of 42 Wh/kg and a peak power density of 100 W/kg.

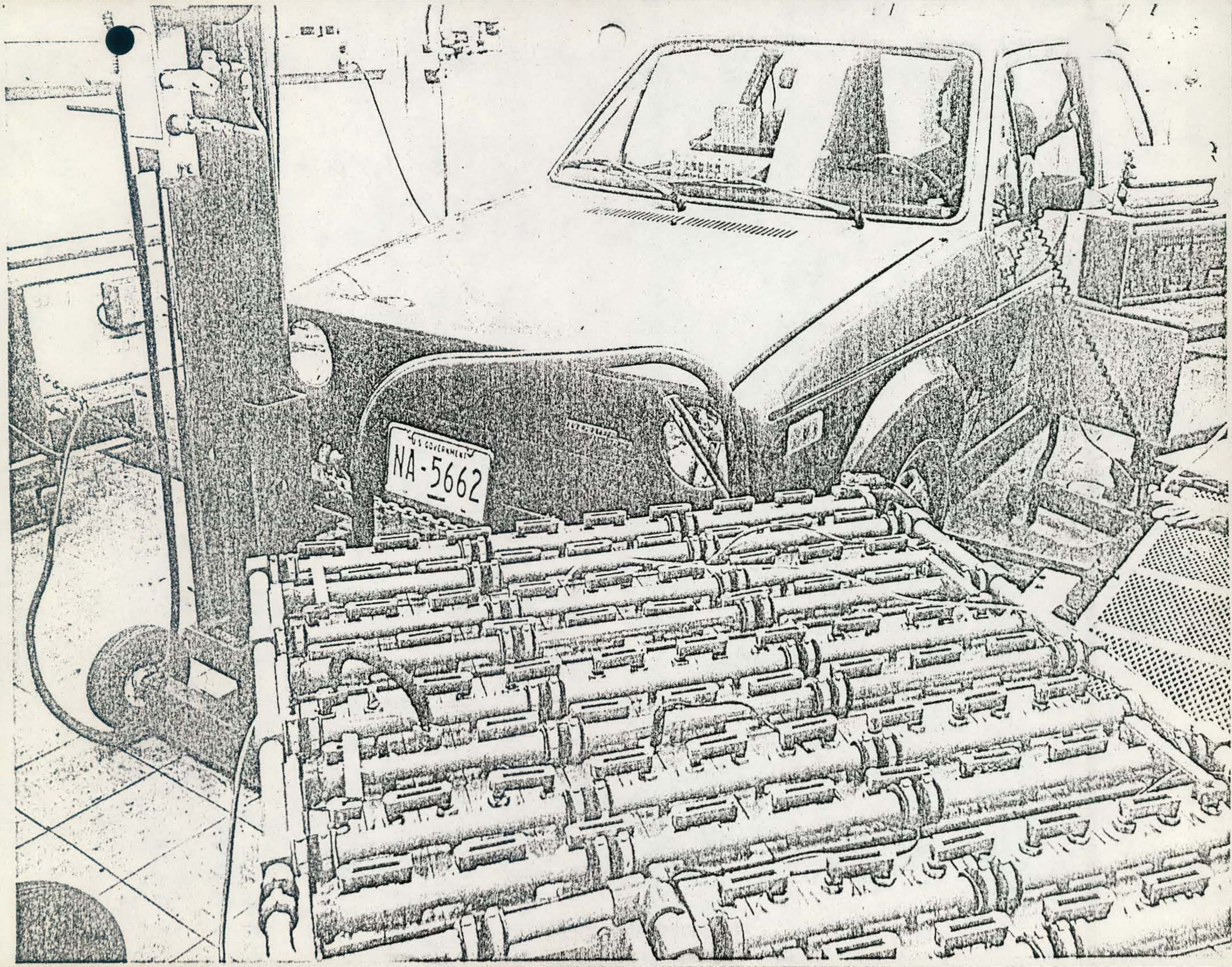
The specific energy of 30 A-hr size Ni/Zn cells tested at Yardney was about 70 Wh/kg, with a life of 130 cycles at 80% depth of discharge (31). However, the performance of six, four-cell, modules (250 Ah) which Yardney delivered to NBTL was less encouraging. Although a specific energy of 62 Wh/kg was demonstrated, cycle life was limited to 38 cycles. It appears that the failure mechanisms of zinc penetration and imbalanced electrolyte distribution are accelerated in Yardney large cells.

One aspect of the DOE/ANL program is to maintain an ongoing effort to ensure that any promising technology is further investigated. Accordingly, five, 4-cell, Ni/Zn modules (225 Ah) were procured from Eagle-Picher Industries for testing at NBTL. These modules displayed a specific energy of 50 Wh/kg; cycle life was limited to 61 deep discharge cycles.

In addition to the delivery of modules to NBTL for verification testing, full-size nickel/zinc and nickel/iron battery packs (23-27 Kwh capacity) were delivered to the Jet Propulsion Laboratory (JPL) in 1979 for electric vehicle dynamometer testing (32). Nickel/Zinc batteries were supplied by ERC (Figure 10) and Yardney (Figure 11) and a nickel/iron battery was supplied by Westinghouse (Figure 12). No serious problems were identified in the system interfacing and integration and the actual performance of the battery packs correlated well with ANL predictions based upon NBTL driving cycle simulation tests of the respective cell modules.




Yardney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V. Remaining Developmental Problem Areas

From Table V one can see that the energy densities of all contractor's lead-acid modules have reached the ISOA goal (40 Wh/kg). However, the cycle life of these modules is far from the expected value of 800 cycles. Since this program is a continuous developmental effort, technology for making better battery is ever improving. The data presented in Table V represent the technology of about one year ago. Since that time, all contractors have concentrated their efforts to improve battery cycle life. There is now reason to believe that some contractor has acquired the technology for making a battery which has both high energy density and longer cycle life. The 800 cycle life of ISOA battery goal is within reach. Recent data from one contractor indicates that cell made with the same construction as that of the ISOA but discharged at 70% depth of discharge has reached over 950 cycles at 3-hr discharge rate.

The modules all the contractors are making today will have a better cycle life than that made before. All the modules made now are being tested. It takes time to obtain the cycle life data. In addition, full-size (25 kWh) vehicle batteries representing the technology of today are under construction at each contractors' plant. These batteries will be delivered to ANL and JPL for simulated and actual vehicle testing.

For the advanced lead-acid battery, all contractors are conducting a separate development project concurrent with the ISOA battery project. Much knowledge obtained from the ISOA project could be of benefit to the advanced battery development. The original goals of energy density 55 Wh/kg and cycle life of 1000 seem too ambitious for the contractors to achieve without significantly increasing the utilization of the active materials and keeping the character of long cycle life. The duration of the contract is a little bit short for research on revolutionary ideas to obtain the knowledge. All the contractors are concentrating their efforts on the best optimization of the known parameters. At the end of the program, the goal for the advanced battery may not be completely reached, a battery with a higher energy density than the ISOA battery and a long cycle life could be obtained.

For nickel/iron batteries R&D problem areas currently being addressed are 1) initial cost reduction, 2) cycle life demonstration with lowered maintenance requirements, 3) thermal management, and 4) demonstration of sufficient specific energy and power to meet acceptable performance for commuter vehicles. The initial cost, cycle life, and maintenance requirements join to result in a need for low life cycle cost in order for this system to become commercially attractive. One ANL contractor (Westinghouse) uses an electrolyte and gas management maintenance system in conjunction with their nickel/iron battery to lower maintenance requirements. This system, which features circulating electrolyte and single-point watering, can either be carried on-board the vehicle, or off-board (only attached during battery charge). Westinghouse too, is particularly sensitiive to initial battery costs as shown by their development of electrode processes which are suitable for low cost, volume production methods. The Westinghouse battery design has evolved, during the current research and development contract, to the point where there is some confidence that the minimum acceptable performance goals can be achieved. However, a number of problems associated with cell assembly and integration of the electrolyte circulation system remain to be resolved. These problems will be receiving the proper engineering emphasis during 1980.

Eagle-Picher has made considerable progress toward the development of a thick (>2.0mm) sintered nickel electrode. Work continues to refine this electrode in order to achieve nickel active material utilizations of over 90% (or 0.26 Ah/g) in a nickel/iron cell. Swedish National Development Co. (Eagle-Picher's iron electrode supplier and partner) has been able to reduce the thickness of the press-sintered iron electrode to 1.2mm while maintaining adequate physical integrety and iron active material utilizations exceeding 0.9 Ah/cc. Swedish National is also carefully investigating the role of additives on enhancing iron electrode life and performance over the temperature range of 0-40°C. This work should result in even further improvements in iron electrode performance. Eagle-Picher is now in the process of designing and procuring cell cases which can be more easily mass produced and assembled into modules. Also, they are studying the thermal management and maintenance needs closely. As a result of this work, a full-sized electric vehicle battery pack will be designed and fabricated during 1980.

R&D problem areas currently regarded as having the most significant impact on barriers to commercial development of the nickel/zinc battery are 1) short cycle life, 2) cost reduction, 3) sealed cell development and 4) thermal management. The lifetime problem is jointly related to separator degradation and the zinc electrode characteristics of dendrite formation and shape change. Early work on separators was focused on cellulosic plastics such as cellophane. However, these were found to be gradually degraded by the cell environment. More advanced inorganic/organic composites and cross-linked organic separators have proven to be more hydroxide resistance. Current efforts are concentrated on developing stable, zinc-free separators which have low ionic resistance ($<0.5\Omega cm^2$) and can be produced at low cost ($<\$0.20/ft.^2$). A number of additives --

both to the zinc electrode and to the electrolyte -- are also being investigated in an attempt to extend cycle life. The role of the additives is to alter the characteristics of zinc dissolution and deposition in such a way to suppress dendrite formation and shape change. By providing dispersed nucleation sites, some additives reduce the extent of zinc redistribution. Others reduce zincate colubility in the electrolyte. Still other additives affect zinc deposition characteristics by raising or lowering the overpotential for the competing hydrogen-evolution reaction. A recent novel approach to reducing shape change has been an attempt to immobilize or otherwise confine species within an inert electrode material. Taken collectively, these new concepts offer substantial reason to believe that improvements in cycle life will be forthcoming.

VI. Prospects of a Commercial Market for Near-Term Electric Vehicle Batteries

As nickel/zinc and nickel/iron designs evolve, the potential market size becomes increasingly important as an influence on corporate commitments to further research and development and capital allocations for pilot production. Estimates of electric vehicles market size differ quite markedly because of uncertainties about future EV performance and cost, future energy availability and cost, and other exogenous factors -- such as shifting consumer acceptance and federal energy policy. Predictions of EV passenger car usage in the year 2000 range from 3 to 24 million vehicles (33, 34). Table VI presents the range of estimates for totals EV's and EV sales per year predicted under various low, medium, and high growth rate market scenarios. Within this context, nickel/zinc and nickel/iron batteries can be portrayed as intermediate-term battery systems capable of capturing a dominant segment of the EV market beginning in the late 1980's, after an initial introduction of lead-acid powered vehicles, and before the more advanced batteries become widely available(35).

Table VI

ELECTRIC VEHICLE MARKET SCENARIOS

Year	SRI* Study	ANL** Low	ANL** Medium	ANL** High
Total Electric Vehicles (thousands)				
1985	-	54	85	168
1990	-	211	410	955
2000	-	3000	8000	24000
Total Electric Vehicle Sales Per Year (thousands)				
1985	10	16	32	70
1990	60	69	154	422
2000	600	961	2900	8340

*Reference 34

**Reference 33

VII. Summary

From the inception of the DOE/ANL Near-Term EV Battery Program in 1978, significant progress in lead-acid, nickel/iron and nickel/zinc battery technology has been made towards achieving the technical performance goals necessary for widespread use of these battery systems in electric vehicle applications. The lead-acid EV battery development has made advances in increasing the energy density from 25-30 Wh/kg to over 40 Wh/kg. Current emphasis is the improvement of cycle life of the high energy density battery to a level of 800 cycles. The prospect for obtaining a lead-acid battery having both high energy density and long cycle life in a few years is very promising. Nickel/iron modules have demonstrated a specific energy of nearly 50 Wh/kg and a specific power of 100 W/kg. Indications are that improved performance in these areas can be shown during 1980. Nickel/iron modules cycle lives of 300 have been achieved during early 1980 and testing continues. Energy efficiency has been improved from less than 50% to over 65%. Nickel/zinc module test data have shown a specific energy of nearly 70 Wh/kg and a specific power of 130 W/kg. However, cycle life improvements are still needed (presently demonstrated capability of 120 cycles) and are expected to be achieved during 1980. Cost reduction (both initial and operating) continues to receive major emphasis at developers of both nickel/zinc and nickel/iron batteries in order to achieve the lowest possible life cycle cost to the battery user.

Based on the continued demonstration of viable solutions to technical problems in the 1980-1983 time-frame, these near-term batteries will emerge as contenders for electric vehicle applications. The relative cost/performance/

life tradeoff of these battery systems continues to receive emphasis in the DOE/ANL R&D Program. While it would be premature at the present time to select winning systems or specific technical approaches, it is the intent of the DOE/ANL program management to continue supporting the development of the most viable approaches in response to the 1986 commercialization goal.

Acknowledgement

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FIGURE CAPTIONS

1. The Four-Passenger DOE Electric Test Vehicle (ETV-1) Designed and Fabricated by General Electric/Chrysler.
2. Two Gould 400 Ah, 4-cell Ni/Zn Modules Under Test in NBTL.
3. An ERC (Energy Research Corporation) 250-Ah, 4-Cell, Ni/Zn Module, With Charge Controller, Under Test in NBTL.
4. An ESB 300-Ah, 4-Cell, Ni/Zn Module Based Upon the Vibrating Electrode Concept.
5. An Engineer Adjusts the Flow Rate in an Electrolyte Circulation System for a Westinghouse 220-Ah, 6-Cell Ni/Fe Module Under Test in NBTL.
6. An Air-Cooled Eagle-Picher 280-Ah, 5-cell, Ni/Fe Module Under Test in NBTL.
7. A Globe-Union 250-Ah Improved Lead-Acid Cell.
8. Two ESB 180-Ah, 3-Cell Improved Lead-Acid Modules Under Test in the NBTL.
9. An Eltra (C&D) 186-Ah, 3-Cell Improved Lead-Acid Module Under Test in the NBTL.
10. The 108 Volts, 250-Ah ERC Ni/Zn Battery (66 Cells) Delivered to JPL for Vehicle Testing. Battery Weight, 1210 lbs.
11. The 108 Volts, 250-Ah Yardney Ni/Zn Battery (66 Cells) Tested at JPL. Battery Weight, 1152 lbs.
12. The 108 Volts, 210-Ah Westinghouse Ni/Fe Battery (90 Cells) Tested at JPL. Battery Weight, 1080 lbs.

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