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THERMAL DISTRIBUTION AND UTILIZATION: AN INTERIM PROGRESS REPORT

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ABSTRACT

This is the first of a series of reports describing technical progress of a research program titled Thermal Distribution and Utilization, sponsored by the U.S. Department of Energy. The subject of the research is the building systems used to distribute heat and cooling from central equipment to building spaces, and the control of these systems to provide thermal comfort while minimizing the expenditure of primary energy. This report describes the 1985 plan of work, and reports on technical progress through January 1985. An introductory section outlines the energy-impact projections upon which the program is based.

INTRODUCTION

Thermal distribution systems comprise the portion of a building system that is used to convey thermal energy in the form of heat or cooling from the central equipment to the building subspaces. Currently, forced-air distribution systems, in which air is driven by fans through duct work, are by far the most popular type in U.S. residential applications, largely because of their compatibility with air-to-air heat pumps and air conditioners. Hydronic systems, which utilize water as the heat-transport medium, retain a niche in the U.S., largely in the Northeast, and are the most popular system in Europe. Radiant systems remain in an early stage of application.

Thermal utilization is defined as the control of the equipment and distribution hardware to provide comfort to the building occupants. The economy of input energy required to provide this comfort is the thermal performance.

The concept of thermal performance, which relates the number of person-hours of thermal comfort provided to the energy content of the fuel required, is a more meaningful figure of merit than thermal efficiency, which does not take into account the many ways that heat or cooling can be wasted after it is produced. This concept has evolved during discussions of thermal distribution systems both within the U.S. Department of Energy (DOE) and among representatives of the broader academic and industry community over the past year and a half. The concept of thermal performance is now established as the guiding principle for a developing program of research titled Thermal Distribution and Utilization, to be sponsored by the DOE.

The need for research on thermal distribution systems is attested by the estimated energy savings available from the technical advances resulting from a successful program--as much as 3.7 quads annually. This research will bridge the gap between improvements in building equipment efficiency and in building envelope thermal integrity. Together, advances in all three areas will provide for optimal mixes of energy conservation options in all situations.

This is the first of a series of reports on technical progress of the program. Because it is the first, it includes some introductory material on energy use impacts and advisory group recommendations. It then presents the work plan for the next year, followed by a progress report for the first four months of this fiscal year.

CURRENT ENERGY USE AND POTENTIAL FOR SAVINGS

Energy Use Patterns

To provide some background for this work and its place in the overall U.S energy use picture, the breakdown of energy use into sectors is reviewed. In 1983, overall consumption of primary energy in the U.S. was 72 quads (1 quad = 10^{15} Btu). This was split [1] into the three major energy-using sectors of the economy as shown in Figure 1. The 26.3 quads consumed by the residential and commercial sector (hereafter called "buildings," although it does not include industrial buildings) was split by source as shown in Figure 2.

The use of natural gas and fuel oil for space heating is expected, but the large usage of electricity may seem surprising. This usage is high (1) because about three units of primary energy are consumed for each unit of electricity delivered to the end user, and (2) because electricity in buildings has other uses besides space and water heating. Of the total 15.92 quads, Figure 3 shows 4.38 quads used for space heating and water heating, and the rest used for space cooling, lighting, appliances, and other.

The three most popular types of electricity-based space conditioning systems in residences are baseboard resistance heat (often supplemented by room air conditioners); central warm-air furnace (often supplemented by a central air conditioning unit); and the heat pump (with its built-in cooling capability). The latter two are warm-air distribution systems, and function in the house in much the same way as a fuel-fired furnace (though heat pumps do have some special characteristics). Thus, energy conservation strategies for warm-air distribution systems need to encompass both electric and fuel-fired systems, and they need to accommodate cooling, which at present is accomplished almost exclusively by electricity-powered vapor-compression equipment.

Most of the oil and gas used in residential and commercial buildings is used for space heating and water heating (8.68 quads). Other uses include cooking and air conditioning (in commercial buildings). Figure 4 shows that

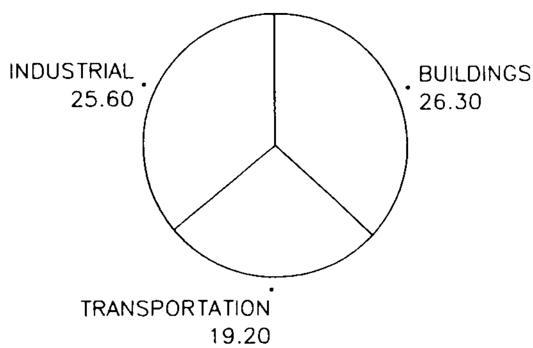

Figure 1. Overall energy use (quads) by sector.

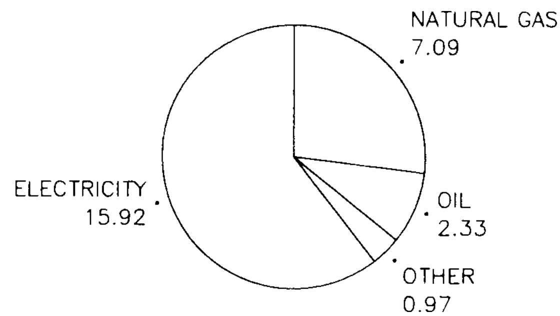

Figure 2. Primary energy use (quads) by the residential and commercial buildings sector.

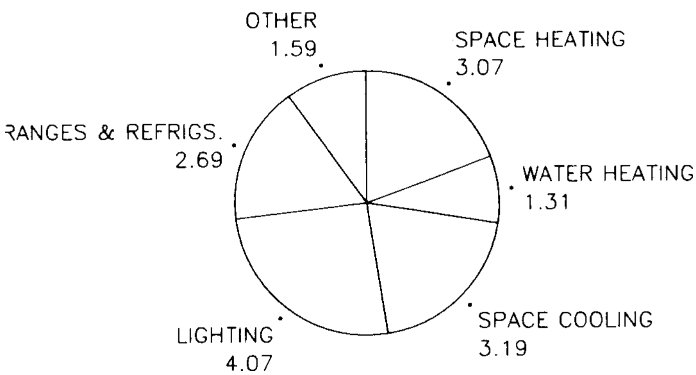

Figure 3. Primary energy (quads) devoted to electricity production for buildings.

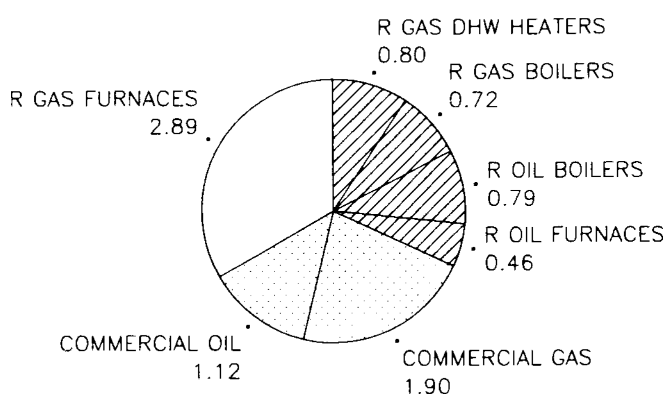

Figure 4. Oil and gas space and water heating (quads) in residential and commercial buildings.

the 8.68 quads is divided into three nearly equal segments: residential gas furnaces, other residential oil and gas use, and commercial oil and gas use. [1-3]. The fact that residential gas furnaces form a major category by themselves highlights their importance in energy use, but it also highlights the importance of forced-warm-air distribution systems, with which they are associated. Commercial energy use is split between gas and oil in about a 5 to 3 ratio. Other residential uses fall into four roughly equal categories: gas water heaters; gas boilers; oil boilers and water heaters (a single category because often one unit serves both functions); and oil furnaces.

Energy Savings Potential

In estimating the potential for energy savings obtainable by developing advanced distribution systems and thermal comfort management strategies, first the effects on systems based on combustion equipment are studied, and then the added impact of applications to electricity-based systems. Current energy use figures serve as a baseline. A rise in the number of applications is expected in the future, which would tend to increase energy use (and hence potential energy savings), but improvement of building envelope thermal integrity is also expected, which would reduce potential savings. The estimates are made with the assumption that these two effects roughly cancel.

The projections are based on general application of the new technologies, with essentially complete market penetration. This will not be achieved for some time, if ever. The estimates serve to give an idea of what is possible.

Treatment of Successive Energy Conservation Strategies. In order to treat the energy savings potential of a number of R&D activities, it is necessary to account properly for the savings resulting from their successive application. The savings are not directly additive, as illustrated by the old joke about the man who installed four different devices on his car, each of which promised to save 30% on fuel, and soon had gasoline overflowing from his tank.

The energy savings potential of an option is characterized by a fractional savings (S), which, when multiplied by the total energy use in the absence of the option, gives the energy use after the option is applied. (The percent energy savings is S x 100). If two options having savings S_1 and S_2, are applied simultaneously, and if their effects are independent (neither synergistic nor redundant), then the percent energy savings will be $(S_1 + S_2 - S_1S_2) \times 100$. Note that this is always less than the sum of the individual savings $(S_1 + S_2) \times 100$. Thus, two options, each of which saves 25%, when applied together save $[0.25 + 0.25 - (0.25)(0.25)] \times 100 = 44\%$, not 50%. Three such options would save 58%, not 75%, and four would save 68%, not 100%. More importantly, the marginal impact of each succeeding option is reduced; in the last example, the marginal savings of the fourth option is only 10% and not 25% of the original total. Here the benefits from advanced distribution systems and thermal comfort management are treated as being logically subsequent to equipment efficiency improvements but not to building thermal envelope improvements. In the final analysis, the optimal treatment of equipment, distribution, and envelope options will be governed by the costs involved as well as by considerations of reliability, convenience, and comfort.

Residential Gas Furnaces. It is estimated that the 2.89 quads of primary energy used in residential gas furnaces is currently utilized at a seasonal efficiency of ∿65%. A great deal of R&D has been undertaken under both government and private sponsorship to improve this efficiency, and the technology to do so has moved to the commercialization phase. Generally, improvements are envisioned as occurring in two stages. The first is to improve heat exchange and reduce excess combustion air so that flue-gas temperatures are reduced to the 300° to 350°F range. This is enough to improve seasonal efficiency to the 80% range if off-cycle aspiration and jacket losses are controlled, but stops short of the temperature regime in which corrosive combustion products begin to condense in vent pipes and chimneys. The second stage addresses the problems of condensation, but extracts the higher heating value of the fuel by reducing flue-gas temperatures below 120°F, with seasonal efficiencies >90%. At present the marginal cost of saving a Btu is greater in the second stage is greater than in the first.[4] The cost effectiveness of the first stage is generally accepted, in most applications. That of the second has been the subject of lively debate in the technical literature and the trade press.

The fractional energy savings for the first stage of equipment efficiency improvement is $1 - 0.65/0.80 = 0.19$, and that for the second stage is conservatively estimated as $1 - 0.80/0.92 = 0.13$. This represents the practical limit of what can be done by equipment efficiency improvement alone. Further improvement in system efficiency can, however, be effected--again, in two stages.

The first stage of system efficiency improvement is to reduce the thermal losses in the duct work. These losses arise from air leakage and heat transfer. Heat transfer losses arise from steady-state convective and radiative heat transfer from the warmer duct work to the cooler surroundings. There are no consensus estimates of the magnitudes of these losses in typical installations, but there are strong indications that they are significant. Previous research projects have found duct losses as high as 50% (see Technical Status, subtask 1A, below). Here, it is assumed that these losses average ∿25%, and that a balanced program of research, particularly directed toward retrofit applications, could cut these losses in half, for a fractional savings of ∿12%.

The second state of system efficiency improvement comprises strategies utilizing spatial and temporal zoning, radiant heating and cooling, and optimal integration of the space heating system into the structure. The use of occupancy-based space conditioning approaches has the potential for energy use reductions in the 30 to 50% range, as indicated by recent work.[5] Here, 30% is adopted as a conservative estimate.

The impact of these improvements on energy use in residential gas furnaces is shown in the first column of Table 1. The 2.04 quad figure was obtained by applying the equipment improvement savings of 19% and 13% to the original energy use figure. Further savings of 12% and 30% yielded the third value of 1.26 quads.

Other Residential Uses of Oil and Gas. Oil furnaces, oil boilers, gas boilers, and gas water heaters have in common the characteristic that each has at least one technical impediment to condensing operation not encountered in gas furnaces. Corrosion problems are more severe in oil units than in gas units, and may be compounded by sooting. Boilers and water heaters as normally operated utilize return- or standing-water temperatures too high to support condensing. Although work is proceeding to make condensing operation possible even in these cases, here only the first equipment improvement savings of 19% is applied reflecting the advance in efficiency from 65% to 80% but not the second advance to 92%, which would require condensing operation.

Strategies for further improvement will depend on the particular equipment type. Oil furnaces are similar to gas furnaces with respect to their distribution system, and therefore the same improvements and energy savings can be projected for duct loss reduction and advanced conservation strategies. Boilers utilize hydronic distribution systems, for which the losses are thought to be significantly lower than for warm-air systems. Although research could probably produce some improvements, no credit for these is assumed here. Advanced conservation strategies can, however, be employed, in some respects more easily and more flexibly than with forced-air systems. (The incorporation of radiant components appears particularly attractive.) Thus, a 30% energy savings is projected for these systems, due to the development of spatial and temporal zoning, improved thermal comfort criteria, and system integration strategies, as it was for forced-air.

Gas water heaters can benefit from integration into the space heating system. Most of these are used in conjunction with a gas furnace. The use of a single burner for both functions with successive heat transfer could greatly increase the seasonal efficiency of the water heating function. A 25% improvement in seasonal efficiency is assumed.

The overall savings for this group of systems, computed on a weighted-average basis, is 30%. The second column of Table 1 shows the resulting energy use figures.

Oil and Gas in Commercial Buildings. Commercial buildings have much larger heating and cooling plants then do residences, usually with a building manager regularly present. This makes it feasible to apply energy-saving concepts that are larger in scale and also require regular maintenance. Condensing economizers capable of raising seasonal equipment efficiency to 95% are possible. If the typical current seasonal efficiency for commercial equipment is taken as 80%, then a fractional savings of $(1 - 0.80/0.95) = 0.16$ would result from equipment improvement.

In the area of advanced distribution and thermal comfort management, a myriad of options have been suggested for fitting the space conditioning more precisely to the human need. Many of these use hydronic radiant panels to meet part or all of the heating load and the sensible portion of the cooling load as well. "Spot" use of radiant panels to provide islands of thermal comfort in buildings where people are relatively stationary and occupy small parts of the space, has also been suggested. The rapid warmup possible with radiant systems makes them ideal for irregular occupancy applications. If R&D causes these systems to gain widespread acceptance, the estimated savings of 30% adopted here could prove highly conservative.

The third column of Table 1 shows the resulting figures for commercial building gas and oil usage.

Electricity-Based Systems. The technology utilized in advanced electric space heating and cooling systems--heat pumps and radiant panels--is more difficult to project than that for combustion systems. Certainly the replacement of electric resistance systems by heat pumps, and the improvement of heat-pump

Table 1
Technical Potential for Energy Savings (Quads)

	Residential gas furnaces	Other residential uses of oil and gas	Commerical oil and gas	Electricity-based heating and cooling
Current usage	2.89	2.77	3.02	7.57
After equipment efficiency improvement	2.04	2.24	2.54	5.18
After advanced distribution and thermal comfort management	1.26	1.57	1.78	3.67
Savings from distribution and thermal comfort advances	0.78	0.67	0.75	1.51

performance in cold cimates (through cycle improvements in air-source heat pumps or the proliferation of ground-source heat pumps) would result in significant energy savings. The application of advanced thermal distribution and utilization concepts to heat pumps and central air conditioning systems has the potential for significant savings. In the case of space heating and cooling, effective means of zoning forced-air systems would be a leading candidate option, as would the integration of radiant with heat-pump heating for irregular occupancy. In the case of water heating, the integration of ventilation heat recovery and space cooling with water heating is a very promising option.

To estimate the potential for savings, the following data[3] may be useful. Of the 14.2 million housing units heated by electricity, 7.8 million have central warm-air distribution systems (5.1 million electric furnaces and 2.7 million heat pumps), but 3.8 million of the furnaces and 2.2 million of the heat pumps are in locations with <4000 heating degree days. Thus, at present the bulk of the electric heating load appears to be met by resistance baseboard.

Regarding air conditioning, the current housing stock has 22.4 million units with central AC, 26.0 million with room AC only, and 34.7 units with none. The trend, however, is unmistakably toward central air conditioning; >50% of houses built in the last 5 years have it. Thus, strategies employing zoning and radiant cooling may have an unexpectedly large impact in the future.

In computing the potential for energy savings in electric systems, it is assumed that most residential installations will ultimately utilize advanced heat pump technology; that radiant panel heating will also penetrate the market at some significant level; but that straight resistance heating will largely be phased out. Heat pumps achieve enhanced efficiency by drawing "free" heat from an environmental source. Radiant systems are no more efficient than resistance on a Btu basis, but they can reduce the demand for energy by providing comfort at lower room ambient temperatures and by being compatible with advanced zoning strategies.

In the U.S., ∿4 million heat pumps were shipped between 1975 and 1984, primarily for residential applications.[6] From 1975 to 1977, annual shipments rose dramatically, from <150,000 units to $\sim$500,000. Four million is used here as an estimate of heat pumps now in place, with units sold before 1975 assumed to balance those taken out of service since then. This compares with a total of 17 million electrically heated households.

On this basis a computation was made of the primary energy needed for residential space heating if all were heated with heat pumps having an effective coefficient of performance (COP) of 2.0, corresponding to an equipment COP of 2.5 (which may be an upper economic limit, though not the technical limit), and 20% duct losses. The 2.06 quads currently used for residential space heating would then be reduced to 1.16 quads. If these duct losses are reduced by half through advanced distribution system technology, the primary energy used will be further reduced to 1.04 quads. And if the application of zoning schemes and system integration produces a further 30% reduction, in line with the discussion of forced-air furnaces, the usage will be reduced to 0.73 quads.

Commercial building space heating via electricity used 1.01 quads of primary energy in 1983. Since commercial building equipment has tended to be more efficient than residential, the equipment efficiency improvement potential was taken as 20%, to 0.81 quads. Applying the same reductions as previously for loss reduction and advanced-distribution/comfort-management, 12% and 30% respectively, gives a potential usage of 0.50 quads.

Space cooling used 3.19 quads in 1983. Here the potential for equipment efficiency improvement was judged to be somewhat greater, at 30%, because of the potential for improved management of latent cooling loads. If achieved, this would reduce primary energy demand to 2.23 quads. On the other hand, the potential for cooling savings through advanced thermal distribution and utilization concepts was set at only 20%, because of the greater time required to bring spaces rapidly from an unconditioned to a conditioned environment when humidity is high, and because of smaller temperature differences between conditioned spaces and the outside ambient. This assumption yields an ultimate potential usage for space cooling of 1.78 quads.

Electric water heating used 1.31 quads in 1983, almost entirely in residences. Most electric water heating is done via direct resistance, the penetration of heat pump water heaters (HPWH) being very low. HPWH's have the potential of cutting this energy usage by a factor of two or more, but a problem, especially in colder climates, is provision of a suitable heat-pump source. We assume here that half of the potential energy use reduction from HPWH's (to 0.98 quads) can be achieved by means of the primary equipment alone (air-source in warmer climates with some earth coupling a possibility elsewhere) but that the other half (to 0.66 quads) will require integration with the rest of the heating and cooling system, with exfiltration air being a primary source.

The last column of Table 1 shows the relevant figures for electricity-powered systems.

Overall Savings. The estimated annual savings from general and complete implementation of advanced thermal distribution and utilization concepts is the sum of row 2 minus the sum of row 3 in Table 1. This is equal to 3.7 quads. At $5 per million Btu, the value of this amount of energy is $18 billion annually.

ADVISORY GROUP RECOMMENDATIONS

Three recent meetings of researchers, program managers, and industry experts held under government sponsorship are especially germane to the topic of advanced distribution systems and thermal comfort management:

1. A workshop on space conditioning research at Reston, Virginia, in December 1982, [7] sponsored by U.S. Department of Energy. Attendance ~50. (The Reston Workshop.)
2. A building energy equipment workshop held at Airlie House, Virginia, in December 1983, [8] sponsored by Committee on Science and Technology, U.S. House of Representatives. Attendance ~50. (The Airlie House Workshop.)
3. A workshop on advanced distribution systems and thermal comfort management, at DOE Headquarters, in May 1984 sponsored by U.S. Department of Energy. Attendance ~20. (The Forrestal Workshop.)

The first two meetings addressed building equipment problems in general, including advanced thermal distribution and utilization concepts; the third was devoted specifically to this topic. The Forrestal Workshop is expected to form the basis for a continuing process of planning and advice from experts not directly associated with the U.S. DOE.

The report on the Reston Workshop distilled out twenty recommendations for future research on building equipment, mostly related to overall system performance prediction, optimization, and standardization, i.e., system integration. Three recommendations related specificially to advanced thermal distribution and utilization concepts:

- o Assess methods of providing zoned heating in residences and commercial buildings.
- o Develop improved comfort criteria based on temperature, mean radiant temperature, humidity, air velocity, air quality, and age of occupants.
- o Develop low-temperature hydronic distribution systems.

The Airlie House Workshop was organized into separate commercial and residential panels. The commercial panel made several general recommendations concerning system design tools, research program assessment, and technology transfer. It also made several specific recommendations for government-sponsored research on advanced thermal distribution and utilization concepts:

- o Develop improved distribution system configurations to offer better temperature and humidity control including matching temperatures to load, so as to maximize the energy efficiency of the total system.
- o Develop improved indoor environmental control technology.
- o Develop improved energy transport and storage technology.
- o Develop dynamic building control strategies.
- o Develop low cost sub-metering.
- o Develop improved heat recovery technology.
- o Develop advanced electronic control technologies.

In the residential area, a subpanel on combustion-fired equipment and appliances recommended research on both warm-air and hydronic distribution systems to optimize energy savings through integration of residential heating and cooling systems and building structures. A subpanel on electrical equipment and appliances listed energy distribution and management systems as a major area for both industry- and government-sponsored research.

The Forrestal Workshop related specifically to the subject of this report. In this case (unlike the other two) a follow-up survey form was sent to the eleven invited experts (not associated with the DOE or the laboratories that organized the workshop) to quantify their opinions of the proposed research topics; ten responded. For the following research areas, a majority indicated that the work is very important or critical, and that government support is appropriate and desirable.

- Develop practical design guidelines for forced-air systems in residences to minimize loss factors.
- Develop retrofit technologies to minimize duct leakage.
- Evaluate zoning in residential forced-air systems, including modulating furnaces, variable air volume, and damper controls.
- Evaluate occupant behavioral aspects of energy conservation strategies.
- Investigate combinations of environmental variables to determine ways to achieve thermal comfort at reduced energy costs.
- Monitor commercial buildings to provide a data base of real-world performance with respect to thermal comfort and energy consumption.
- Evaluate energy savings potential and comfort characteristics of localized heating and cooling schemes in commercial and industrial buildings.
- Evaluate energy savings potential of occupancy-based or adaptive control systems relative to preprogrammed control systems.
- Evaluate potential energy savings and comfort aspects of multiple-evaporator heat pumps.
- Evaluate air-quality sensors.

In addition, activities in the area of information management and technology transfer received strong support from the participants.

In seeking common threads running through the three meetings, the following points can be made.

- The possibility of improving system performace through improved comfort criteria incorporating variables other than air temperature and relative humidity, and treating time-varying conditions, was recognized explicitly and strongly.
- In residential forced-air systems, zoning and loss reduction were seen as two major avenues to energy conservation.
- The need for integration of equipment, distribution, and envelope subsystems was recognized.
- The need for information management and technology transfer was emphasized and the appropriateness of a government role was generally accepted.
- The proposed research activities, though diverse, all had one or more of the following objectives:
  1. Minimize energy transport losses.
  2. Reduce demand for comfort conditioning through temporal or spatial zoning.
  3. Utilize improved thermal comfort criteria to provide acceptable comfort with reduced expenditure of energy.
  4. Influence occupant behavior as it relates to energy use.
  5. Effect distribution system design changes that will result in equipment efficiency improvement.

6. Recover unutilized or waste heat.
7. Provide distribution system designs that are jointly optimized with the building envelope.

The program activities outlined in the next section seek, to the greatest extent possible, to incorporate these recommendations (as well as others that will emerge during the course of the year) into a long-range program of research that will address the fundamental problems and opportunities in the thermal distribution area.

RESEARCH PROGRAM FOR 1985

The major task during 1985 will be to expand the concept of thermal performance into a comprehensive research and development plan for the thermal distribution and utilization subject area. Five tasks and 24 subtasks were identified that will lead to such a plan. In each major task area, a preliminary assessment provides information necessary for program planning and also leads to a reevaluation of national energy savings potential. This is followed by the planning itself, in which research needs and opportunities are decided upon and are then organized into a well articulated planning document. The outline below shows the task organization. This is followed by a schedule and milestones.

1. Loss Reduction in Forced-Air Distribution Systems
   i. Assessment
      A. Gather and organize information on duct losses (subtask 1A)
      B. Get data on housing and duct characteristics (subtask 1B)
      C. Study and compare thermal loss mechanisms (subtask 1C)
      D. Recalculate possible nationwide energy savings (subtask 1D)
   ii. Planning
      E. Formulate potential solutions to the duct loss problem and assess technical feasibility (subtask 1E)
      F. Screen for nontechnical barriers (subtask 1F)
      G. Develop a research plan (subtask 1G)

2. Zoning in Residences with Forced-Air Distribution Systems
   i. Assessment
      A. Gather and organize information on zoning (subtask 2A)
      B. Study interzonal interactions (subtask 2B)
      C. Assess effect of occupant behavior on the energy savings from zoning (subtask 2C)
      D. Recalculate possible nationwide energy savings (subtask 2D)
   ii. Planning
      E. Formulate zoning concepts and determine what research is needed to make them feasible (subtask 2E)
      F. Prepare a research plan (subtask 2F)

3. Hydronic Distribution Systems
   i. Assessment
      A. Gather and organize information on hydronic systems (subtask 3A)
      B. Make a special effort to obtain information on the European experience (subtask 3B)

C. Determine what the major problems are and where there is potential for energy savings (subtask 3C)
D. Calculate possible nationwide energy savings in both retrofit and new construction (subtask 3D)

ii. Planning

E. Determine the major areas of research needed to obtain the energy savings projected above (subtask 3E)
F. Develop a research plan (subtask 3F)

4. Radiant Heating and Cooling Systems

i. Assessment

A. Gather and organize information on radiant systems (subtask 4A)
B. Identify ways of urging radiant heating and cooling to effect significant energy savings in the home (subtask 4B)

ii. Planning

C. Determine what research is needed to exploit the opportunities identified above (subtask 4C)
D. Develop a research plan (subtask 4D)

5. System Integration
This task will use all the information gathered in the preceding tasks to determine whether any important research needs, particularly those involving interactions of the distribution system with the space conditioning equipment or the building envelope, have been overlooked (task 5).

TASK 1. LOSS REDUCTION IN FORCED-AIR DISTRIBUTION SYSTEMS

The potential for energy savings from reduction of losses in forced-air distribution systems has been variously estimated at from 5% to 40%. For FY 1985, work in this area will consist of assessment of the technical area and determination of research needs. Deliverables for the seven subtasks will be incorporated in a formal publication.

Subtask 1A. Technical Evaluation and Literature Search

This subtask will include gathering information on loss mechanisms in forced-air distribution systems, methods of loss reduction, retrofit materials and techniques, and new commercially available distribution systems. This information will be evaluated to determine areas that have not been investigated, promising research, and promising products. The deliverable for this task will be a summary of state-of-the-art forced-air distribution systems design.

Subtask 1B. Determine Relative Frequency of Generic Housing Types

Data will be gathered on housing types, heating and cooling systems, and distribution systems, from sources such as the Energy Information Agency and the National Association of Homebuilders. The data will be used to assess the energy savings potential for loss reduction and zoning of distribution systems. The deliverable will be a set of tables detailing type of distribution system by house type and fuel for each census subregion.

Subtask 1C. Determine Relative Importance of Thermal Losses and Air Leakage for Generic Housing Types and Climates

Based on a detailed review of available research results and other data on ducting losses, a preliminary analysis will be done to identify the relative magnitudes of thermal energy losses in residential air distribution systems, including losses due to direct air leakages, thermal conduction and convection, and induced infiltration associated with air distribution system operation. The evaluations will include a matrix analysis of the losses as a function of generic housing types, climate zones, and ducting distribution types.

Subtask 1D. Reassess Energy Savings Potential

A preliminary assessment of energy savings potential from loss reduction in residential forced-air systems was based on a projected 12% across-the-board improvement. This reassessment will use information obtained as described above on (a) better estimates of overall loss magnitudes, (b) relative importance of various loss mechanisms, and (c) relative frequencies of housing and duct-system types. This information will provide a firmer foundation for the reassessment and will make it easier to spot specific areas where most significant gains are possible.

Subtask 1E. Formulate Potential Solutions for Retrofit, New Construction, and Diagnostics

Based on the results of efforts to determine the relative importance of different types of thermal losses, literature searches, a survey of available ducting systems and components, and meetings with consultants and ducting industry representatives, a list of possible approaches to eliminating or significantly reducing energy losses in residential ducting systems will be formulated. This list will also include concepts for diagnostic tools to be used with ducting systems (retrofit or new construction) to aid in their proper installation and thus maximize effectiveness of their operation. This list will be reviewed and analyzed by project staff, consultants, and industry representatives, by a qualitative systems analysis technique comprising a series of evaluations by a comparative rating method involving potential for energy savings, potential for application problems, and developmental risk.

The results of this analysis will be combined with the analysis of institutional, economic, environmental, and health issues in subtask 1F to establish priorities among potential solutions and needed diagnostic tools, which will then become part of the detailed research plan for the reduction of losses in residential HVAC ducting systems.

Subtask 1F. Assess Institutional, Economic, Environmental, and Health Issues

Each of the potential solutions identified in the preceding subtask will undergo a screening process to identify potential non-technical issues or barriers to its implementation. Institutional issues include building codes, patent protection problems, variation from industry practice, and potential opposition from defined interest groups. Economic issues include consumer cost and financing and also potential industry production problems. Environmental and health issues include emissions problems, indoor air quality, and safety concerns.

Subtask 1G. Prepare a Research Plan for Residential Forced-Air Loss Reduction

The results of the six preceding subtasks will be used as a data base in preparing a long-term research plan for the reduction of losses in distribution systems. To prepare this plan, a group of collaborators will be assembled to work with BNL personnel on a continuing basis to critique the information gathered in the six subtasks, evaluate the need for further research, and prepare a comprehensive plan for future research.

TASK 2. ZONING IN RESIDENCES WITH FORCED-AIR DISTRIBUTION SYSTEMS

The energy savings to be gained from zoning are well documented, but zoning is not a common strategy in forced-air systems in residences because of technical difficulties and associated costs. During FY 1985 the technical area of residential zoning applied to forced-air systems will be assessed, and a plan for generic research will be developed. Results of the six subtasks will be published in a formal report.

Subtask 2A. Technology Evaluation and Literature Search

This literature search will cover research on interzonal interactions, variable capacity heating and cooling systems, controls for zoning of buildings, and occupant response to zoning. The information will be used to develop the research plan by determining what areas of zoning need to be studied in greater detail and by evaluating the effectiveness of existing commercially available zoning equipment. The deliverable for this task will be a summary of completed zoning research and an evaluation of existing zoning equipment.

Subtask 2B. Study Interzonal Interactions

Within this area of work, generic residential building subspace arrangements will be evaluated to determine their effectiveness for operating at different temperatures to achieve savings through zoning techniques. Simplified energy flow and balance calculations will be used to evaluate the interzonal interactions created by such things as open doorways, hallways, and stairwells, as well as distribution systems. Published data will be correlated with calculated values and, where necessary, simple experiments to determine time constants for loss of interzonal temperature difference. The results of this work will be generic in nature and will be used to support estimates of the savings potential for forced-air residential zoning and will provide the groundwork for establishing specific research issues within the research plan.

Subtask 2C. Assess Occupant Behavior

Behavioral approaches to energy conservation have been effective in studies done by Princeton at Twin Rivers. Occupants' attitudes toward energy, comfort, and health play an important role in energy use. Feedback and control systems can also affect the amount of energy used. In this task, existing work on occupant behavior will be reviewed to determine the effect of occupants on heating and cooling system energy use as it relates to forced-air residential zoning. The deliverable for this task will be a report section outlining the relationship of attitudes to energy use, and recommending equipment controls to help the occupant use less energy for heating and cooling.

Subtask 2D. Determine National Energy Savings Potential from Zoning of Residences with Forced-Air Distribution Systems

A preliminary assessment of energy savings potential from zoning in residences with forced-air distribution systems was based on a projected 30% across-the-board improvement. This reassessment will use information obtained as described above regarding (a) better estimates of potential technology improvement, (b) relative frequency of generic housing types, (c) interzonal interactions, (d) expected occupant behavior patterns. This information will provide a firmer foundation for the reassessment and will point out specific areas where the most significant gains are possible.

Subtask 2E. Identify Technical Approaches and Research Needs

The literature search, technology evaluation, data base development, determination of interzonal interactions, and potential for energy savings analysis will be used as the basis for identifying technical approaches and research needs in the area of forced-air residential zoning. The results of these activities along with a survey of commercial zoning equipment and products will be presented in a concise format that will be the basis of discussion meetings to develop potential technical approaches, in order to identify research needs for efficient zoning for residential air distribution systems.

Subtask 2F. Prepare a Research Plan for Residential Forced-Air Zoning

The results of the five subtasks described above will be used as a data base for the preparation of a long-term research plan for zoning in residences with forced-air distribution systems. To prepare this plan, a group of collaborators will be assembled to work with BNL personnel on a continuing basis to critique the information gathered in the five subtasks, evaluate the need for further research, and prepare a comprehensive plan for future research.

TASK 3. HYDRONIC DISTRIBUTION SYSTEMS

Currently, ~13 million hydronic systems are in place in U.S. residences, mostly in the Northeast. Over the past two decades, new hydronic installations have increasingly lagged behind forced-air. Hence, the overall approach here must take two separate paths. One is to consider the potential for retrofit of existing systems. The other is to consider new construction options, drawing upon the extensive European experience, to determine whether hydronic systems can offer potential energy savings vis-a-vis forced-air systems. Subtasks 3C, 3D, 3E, and 3F will be completed in FY 1986.

Subtask 3A. Technology Evaluation and Literature Search

An organized technology evaluation and literature search in the area of hydronic distribution systems will be conducted. The evaluation will be directed towards methods of improving the efficiency of hydronic convectors, zoning strategies, and controls, and the application of condensing heating plants on a retrofit basis in hydronic systems. This work will form a base for additional planning activities.

Subtask 3B. Evaluate European Research and Practice

An evaluation survey will be conducted to review and analyze the European technologies associated with hydronic heating and hydronic distribution systems and equipment. The first step will be to review reports, research, and product literature available in the U.S. The second step will be to subcontract additional work to one or more organizations that have connections or direct access to the European hydronic heating industries and research organizations. This work will require the documentation and translation of results into a format that can be used in a plannned analysis effort.

Subtask 3C. Identify Problems and Energy Savings Potentials

The technical evaluation and the European technology survey will be studied. Loss mechanisms for hydronic systems will be identified and ranked in importance. Significant loss mechanisms will be examined and conceptual methods of loss reduction will be evaluated. New system concepts will be developed where possible. Retrofit options will be considered with a view toward upgrading the significant number of hydronic systems in place. Options for new construction will be evaluated relative to competing forced-air systems. The result will be a list of system concepts with significant potential for energy savings.

Subtask 3D. Determine National Energy Savings Potential for Hydronic Systems

The technical possibilities for saving energy in hydronic systems identified in preceding subtasks will be evaluated in terms of their potential for energy saving on a national basis. Emphasis will be on retrofit options, because of the much larger number of existing hydronic systems than of new installations, but energy-savings potential for new technology will also be evaluated, vis-a-vis forced-air system options.

Subtask 3E. Identify Research Topics

Various aspects of improved hydronic system technology will be scrutinized to identify generic research needs. The areas of study will involve the accomplishment of significant savings through reduction of losses or other improvement in thermal performance of the building/HVAC system. The various areas will be reviewed by researchers and practitioners and categorized in terms of their applicability to refit or new construction, impact on the equipment and construction industries, and acceptance by code institutions. The results of the work will provide a basis for the development of a research plan.

Subtask 3F. Develop Recommended Research Plan for Hydronic Systems

Based on the results of the previous five tasks, a research plan will be developed. This plan will prioritize research work on hydronic systems according to the criteria of energy savings potential and an evaluation of technical problems.

TASK 4. RADIANT HEATING AND COOLING SYSTEMS

Radiant heating systems based on electric resistance have gained a foothold in residential HVAC practice. Systems driven by direct firing of gas or oil have potential advantages, but have not been implemented in residences in any numbers, although such systems are used in commercial buildings, and often are used for radiant cooling as well as heating. This task will lead to a plan for the performance of generic research as well as some applications-oriented work to enable the homebuilding industry to properly evaluate this technology. Subtasks 4C and 4D will be completed in FY86.

Subtask 4A. Technology Evaluation and Literature Search

Information on radiant heating and cooling systems, radiant effects on thermal comfort, and energy savings potential of radiant systems will be gathered and evaluated to determine research needs in radiant heating and cooling. The deliverable for this task will be a summary of the state-of-the-art in radiant systems, and the status of thermal comfort reseach relating to radiant heating and cooling.

Subtask 4B. Assess the Potential of Radiant Systems

The state-of-the-art assessment will be reviewed. The operational conditions under which radiant systems must function to meet human factor requirements will be delineated. Various conceptual configurations and strategies will be evaluated and ranked in terms of practicality, safety, human factors, and potential savings. These concepts of systems depending on radiant heating and cooling will include both those operating alone and those combined with other types of space conditioning systems. The output of this work will be a list of radiant or hybrid systems with significant energy savings potential for residential and small commercial buildings.

Subtask 4C. Identify Research Needs

The various systems with significant energy savings potential will be examined in some detail to identify areas of required generic research. These areas will be reviewed by appropriate researchers and practitioners and will be categorized in terms of means of implementation, refit vs. new construction, and predicted consumer acceptance. The results of the work will provide a basis for the preparation of a research plan.

Subtask 4D. Prepare a Research Plan for Radiant Systems Research

This activity will result in a detailed plan for future research and development of technology for energy-efficient radiant space heating and cooling in the residential sector. The work will incorporate in a formal plan the results of work in the area of radiant heating technology evaluation, literature searches, assessments of the energy savings potential, and identification of research needs and technical approaches. Details of planned future activities, methods of approach, schedules, cost estimate, and manpower requirements will be included, as well as a discussion of how this project relates to and functions with other planned project areas in the general program area of residential thermal distribution and utilization.

TASK 5. ASSESS NEED FOR SYSTEM INTEGRATION RESEARCH

The major constituents of a building can be disaggregated into (a) building envelope, (b) building sub-spaces, (c) HVAC distribution, and (d) space-conditioning equipment. The planned study of system integration deals with the interactions of building constituents involving the distribution system. This task will determine whether research is needed on system integration that cannot be covered in any of the previous subject areas. Specific issues, having potential for significant energy impacts, and not being dealt with in other programs, will be considered. This task will be completed in FY 1986. (See Figure 5.)

TECHNICAL STATUS AS OF JANUARY 1985

The following sections summarize technical progress and outline plans for future work on the 24 subtasks described in the preceding section.

TASK 1. LOSS REDUCTION IN FORCED-AIR DISTRIBUTION SYSTEMS

Subtask 1A. Technical Evaluation and Literature Search

Published Literature. Information is being gathered about research on loss mechanisms in forced-air distribution systems, methods of loss reduction, retrofit materials and techniques, and new commercially available distribution systems. Several papers germane to the issue of duct-loss magnitudes have been located; these are discussed below.

As early as 1937, the University of Illinois was doing research on heating and cooling systems in residential structures. The work focused on comfort, design optimization, and energy use. More than 40 reports, written from 1937 to 1963, have been obtained which cover pressure losses in duct systems, comparisons of heating systems, and research on heating and cooling distribution systems. The data in these reports may be useful, although house insulation levels and furnace efficiencies have changed drastically since this work began.

Measured Duct Losses. A review measured losses from warm air distribution systems shows that losses from ducts can be as high as 50% of net furnace output. Table 2 summarizes the results of previous work; the listed duct efficiencies are all measured ones. In some work [9-11] the amount of energy delivered through the registers was measured to determine duct efficiency. In other work [12, 13] all heat from the furnace which eventually enters the living space is considered to be not lost by the distribution system. This includes heat lost to the basement which is later transferred to the living space, and conduction gains to the living space through duct walls.

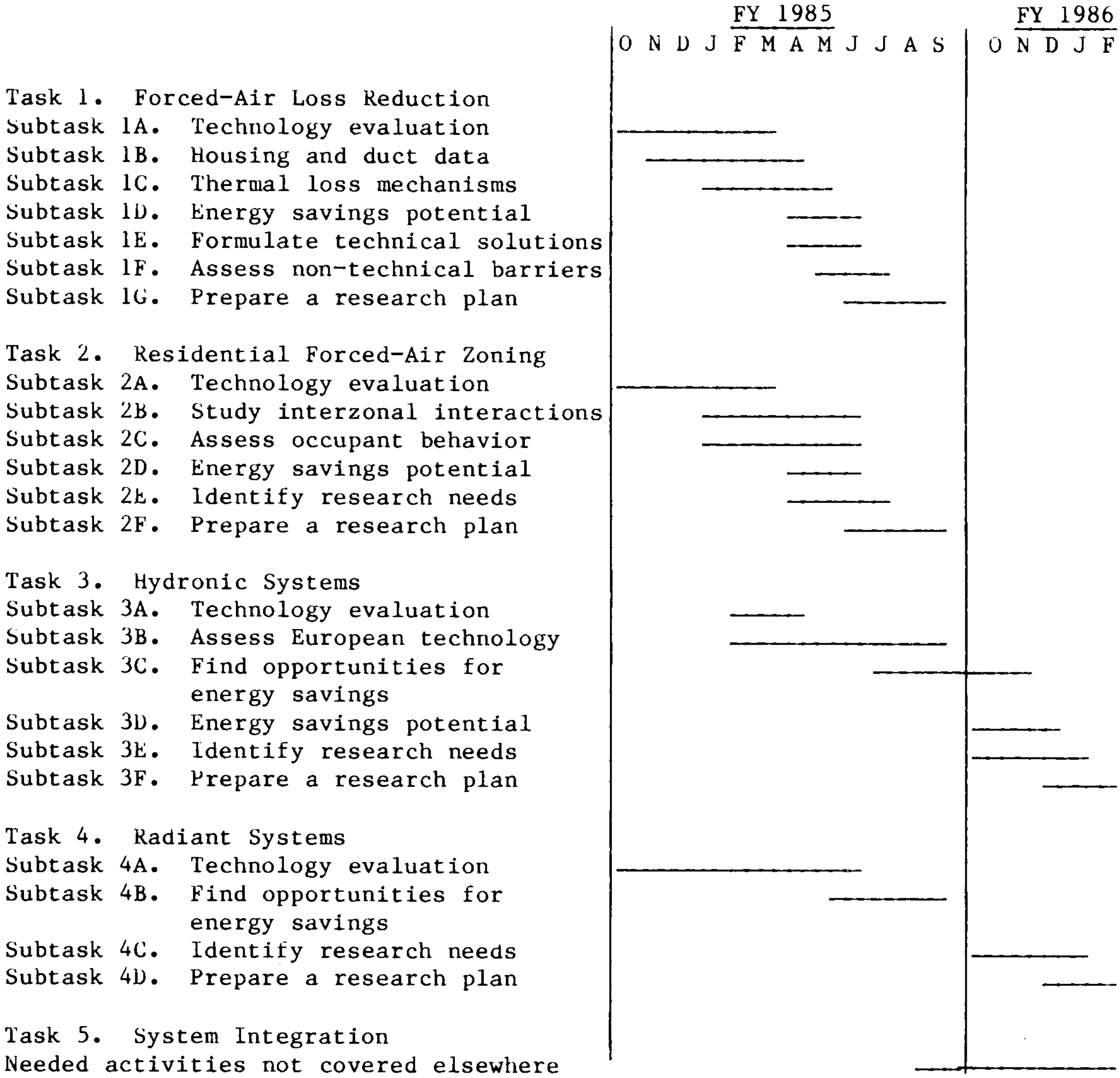

Figure 5. Task organization and timing.

The results Refs. 9 and 10 are measurements of energy delivered from the furnace through the register, taken during a series of tests conducted by Princeton at Twin Rivers townhouses. According to Socolow [9, p.25],

> The entire hot air distribution system delivers only half of its heat to the rooms via the registers, one-third of the heat flowing initially into the basement and one-sixth flowing initially into the interior structure above the basement. Much of the heat not entering the living area through the registers nonetheless heats the living area, and it is not clear whether the flow of heat into the interior of the structure above the basement (in spaces between interior studs, for example) should be avoided.

Table 2
Summary of Previous Work on Duct Losses

Reference	Duct efficiency (% of net furnace output)	Conditions
9	50% at steady state delivered through registers	Two-story townhouse, ducts in basement ceiling and interior walls; 246 ft of duct work; 160 ft in basement, uninsulated ducts.
10	50% at steady state delivered through registers	Same townhouse as in Ref. 9; 25% of net furnace output is lost to unheated space; 25% is delivered indirectly to living space.
11	85% steady state 95% over 15-min cycle	Measured steady-state performance; calculated cyclic performance; duct insulated in crawlspace.
12*	88% (29% of loss is convective) (71% of loss is conductive)	Two-story home w/basement and partial crawlspace; 125 kBtu/hr input, uninsulated ducts in basement, major leaks taped; fan starved.
	82%	Same house as above, uninsulated ducts in basement, not taped, normal operating conditions.
	85%	Bi-level on slab, 130 kBtu/hr input.
	80%	Two-story townhouse w/basement, 80 kBtu/hr input.
	73%	Two-story w/basement, 80 kBtu/hr input.
	89%	Two-story w/basement, 90 kBtu/hr input.
	83%	Ranch w/basement, 137 kBtu/hr input.
13*	Cooling: in basement 91% in attic 50% uninsulated in attic 56% insulated	Two-story w/basement, with ducts in basement and attic; 41.5 kBtu/hr air conditioner.
	74% cooling	One-story w/no basement, slab distribution system; 34 kBtu/hr air conditioner.
	92% cooling 93% heat pump heating 92% furnace	Split-level w/basement; 130 kBtu/hr furnace input heat pump; 34 kBtu/hr heating; 31 kBtu/hr cooling.

*These data are measurements of the entire heat flow from furnace to conditioned space, including flows lost to unconditioned space and eventually transferred to a living space. Therefore, the numbers include indirect heat transfer from the distribution system.

Grot and Harrje [10] give more details on the distribution system studied by Princeton. They insulated a duct system and compared its performance with that of the uninsulated system:

> It was found that although the addition of duct insulation did drop the basement temperature by about 5°F, the profiles of the air exit temperatures at the room registers did not change appreciably and that little additional heat was delivered to the living areas during normal transient furnace operations.

Their explanation for this phenomenon is that, during the short on-cycles common in residential furnaces, the major mechanism for cooling the supply air is heat transfer to the metal of the ducts. During the on-time of the furnace and blower, the duct does not lose a significant amount of heat to the surrounding space but the duct sheet metal stores a significant amount of heat. This stored heat is lost by conduction, convection, and radiation after the blower is shut off.

The heating capacitance of ducts has an effect on when and where energy from the furnace is delivered to the living space. Grot and Harrje [10] concluded from their data that "... during intermittent blower operations, the furnace blower is turning off at a time when many of the ducts are just reaching maximum exit air temperatures." They also found that the duct metal itself removed a sizeable fraction of the heat from the supply air during the first minutes of burner operation.

Nicol [11] measured duct air flow rates and temperatures to determine steady-state duct efficiency. He calculated the cyclic efficiency assuming an exponential drop in efficiency as supply air temperature rises.

GKCO Consultants, [12] using tracer gas to measure air flows from the distribution system, were able to quantify the duct efficiency in seven homes. They give the results of duct loss measurements as percent excess gas use due to duct losses. For presentation in Table 2, the data were converted to duct system efficiencies by the following formula:

$$\text{Duct efficiency} = \frac{1}{\left(\frac{\text{Percent excess gas use}}{100}\right) + 1} .$$

GKCO [12] also showed that the air distribution systems can decrease furnace efficiency by almost 5% by failing to provide adequate return air to the furnace. This can cause reduced heat transfer in the furnace and also increases infiltration in the furnace location from outside or from the conditioned space.

GKCO [13] gave efficiencies for distribution of air for cooling and for heating in the report of a project that followed the above study. [12] The objectives were to measure the distribution system losses from heating and cooling equipment, and to develop a tracer-gas technique to measure duct losses during cooling system operation.

Duct Design Guidelines. Duct design guidelines [14-16] cover pressure drop, duct sizing, balancing and testing, noise vibration, and materials. Air leakage of duct work is addressed in the SMACNA design manual [14, p. 2.4] by the following recommendation:

The sealing of ducts should result in a leakage rate of less than 5% of systems operating at 2 inches or below, and 1% loss in medium and high pressure systems operating from 2 inches to 10 inches. The cost of sealing could be approximately 5% of the duct work first cost. If the designer eliminates the sealing of an average low pressure duct system, (s)he must make an allowance in calculations for a minimum of 15% duct leakage.

Because most residential duct systems are not sealed, this indicates that, according to SMACNA, they have leakage rates of at least 15%.

The NAHB duct design guidelines [15] provide general guidance for builders designing air distribution systems. They present information on duct layout and sizing but do not address duct leakage and losses.

A design manual published in the Netherlands [16] gives rules for layout and design of a duct system for minimum life-cycle costs. Total life-cycle costs include those for the initial duct, for air transport energy (blower energy), for space in the building, and for the loss of heat and cold through the duct walls. The procedures are based on mathematical analyses and computer calculations. The heat gain (or loss, in the cooling mode) from the duct system is assumed to be completely lost, even though it may eventually affect the conditioned space. This design manual is focused on systems in commercial buildings but could be used for residential systems.

Modeling Distribution Systems. Theoretical analyses of duct systems have been done. [10, 17] Harrje and Grot [10] used a mathematical model for the transient response of warm air heating ducts to analyze duct performance and used data from the Twin Rivers townhouses to verify the model with the model they determined when duct temperatures stabilize, and compared the performance of uninsulated ducts and ducts with exterior or interior insulation. They found that internally insulated and uninsulated ducts approach equilibrium temperatures sooner than outside insulated ducts, which take >10 minutes to reach equilibrium. They concluded that leak-free, internally insulated ducts will achieve minimum energy distribution losses and maximum comfort.

Murphy and Goldschmidt [17], measured transient temperatures in a 9.8-ft (3-m) section of poorly insulated duct downstream of an evaporator coil. Their purpose was to measure the effects of placement of a thermocouple grid by mathematical simulation of the evaporator section and duct work. Losses in the evaporator section and duct work are measured and calculated. The model generates temperature profiles of air and duct using an explicit finite difference method. The model also simulates thermocouple and blower temperature response. This model could be used to determine losses in residential air distribution sytems.

Commercially Available Products. In support of project areas covering the warm-air loss reduction and residential zoning in warm-air systems, a survey was initiated to obtain materials and information to provide a background technology evaluation of products, systems, and components that are now commercially available.

The product survey covers 184 potential manufacturers of ducting, ducting materials, components, zoning, devices, and terminal equipment. A letter was sent to each company explaining the general direction of the program efforts and requesting technical information, product information, and related reports on nonproprietary research. Received to date have been 14 positive replies with useful data, 16 replies with product information of some minor relevance, 10 negative replies, and no response from 144 addressees, plus a design manual, "Duct Design for Residential Winter and Summer Air Conditioning and Equipment Selection," sponsored by the Air-Conditioning Contractors of America, and a test standard, "Flexible Air Duct Test Code FD 72-R1," prepared by the Air Diffusion Council, Chicago, Illinois. The various responses are being catalogued and reviewed for use in the studies and program planning efforts in the areas of loss reduction and zoning.

The large number of nonresponses is probably due to erroneous listings in product guides (which provided much of the mailing list) and to old listings of companies that have moved or gone out of business. Also, many listings may have been local sheet metal fabricators who produce only "to specification" and have no available product sheets or information.

The information obtained will be evaluated to determine areas that have not been investigated, promising research, and promising products. Already it is clear that losses in distribution systems have not been quantified. Research in progress at Battelle Columbus Laboratories and the Gas Research Institute may answer some questions about distribution system losses, but no research concentrating on these losses has been found.

Subtask 1B. Determine Relative Frequency of Generic Housing Types

Data on housing types, heating and cooling systems, and distribution systems that are available from the Residential Energy Consumption Survey [3], the Gas Research Institute, and the National Association of Home Builders (NAHB) have been reviewed. After discussions with NAHB, a format for information to be provided by NAHB was chosen. This information will include average length of duct work in each house type for each of the nine census regions, both for the existing housing stock and for new construction. Other information on distribution systems by fuel type will also be detailed. A total of 36 matrix charts will be provided. For each census region, data will be obtained on duct work characteristics and on fuel type by house type, both for existing housing and for new construction (four charts per region). Examples of charts are shown in Figures 6 and 7.

Subtask 1C. Determine Relative Importance of Thermal Losses and Air Leakage for Generic Housing Types and Climates

Four duct loss mechanisms have been identified, in two categories as outlined below.

1. Direct Losses

i. Duct Leakage - Duct leakage losses, also called convective losses, are due to holes, cracks, or open seams in the ducting system which cause direct losses to unconditioned spaces and lead to imbalances in the system's operation.

ii. Duct Heat Transfer Through Duct Walls - Heat transfer losses, sometimes called conductive losses, are actually due to forced convective heat transfer (inside the duct) to the ducting walls, conduction of the heat through the duct wall material(s), and then free convective heat loss off the exterior surfaces of the ducts to the surrounding environment, which in many homes is unconditioned space.

NEW HOUSING STOCK

NEW ENGLAND CENSUS REGION

			Average Length of Duct Work by Location							% of Ducts with Insulation or Fiberglas Ducts						
House Type	Foundation	Number of Homes	Basement (Heated)	Basement (Unheated)	Crawl Space	Attic	Slab	Outside Walls	Inside Walls	Basement (Heated)	Basement (Unheated)	Crawl Space	Attic	Slab	Outside Walls	Inside Walls
Single Story	Full Basement															
	Partial Basement															
	Crawl Space															
	Slab-on-Grade															
Two-Story	Full Basement															
	Partial Basement															
	Crawl Space															
	Slab-on-Grade															
Bi-level	Full Basement															
	Partial Basement															
	Crawl Space															
	Slab-on-Grade															
Split Level	Full Basement															
	Partial Basement															
	Crawl Space															
	Slab-on-Grade															
	Total No. of Homes															

FIGURE 6. Duct work characteristics information matrix.

EXISTING HOUSING STOCK

MIDDLE ATLANTIC CENSUS REGION												
	HEAT DISTRIBUTION SYSTEM BY FUEL TYPE											
	Forced Air				Hydronic				Other			
House Type	Gas	Oil	Electric Furnace	Heat Pump	Gas	Oil	Electric Furnace	Heat Pump	Gas	Oil	Electric Furnace	Heat Pump
Single Story												
Two-Story												
Bi-level												
Split Level												

FIGURE 7. Heat distribution system by fuel type information matrix.

S45

2. Indirect or System Losses

i. Infiltration - Losses due to increased rates of infiltration and exfiltration between living space and outside air are related to operation of the space conditioning system, its imbalance, and duct placement within the structure. These losses result from inadequacies in the return-air system or in the supply ducting systems that cause local negative or positive pressure zones in the structure. The pressures drive air into and out of both conditioned spaces and unconditioned spaces, which are coupled to the outside environment.

ii. Furnace-Efficiency Impacts - Two losses associated with the ducting system are directly related to furnace operation. (1) Inadequate flow of air to the furnace through the return ducts lowers the furnace efficiency because heat exchanger effectiveness decreases with decreased air flow velocity. (2) Excess furnace operating time due to a poorly balanced air-distribution system can allow local overheating of some living areas.

The work of this subtask will concentrate on the direct losses, but some effort will be made to gauge the relative magnitude of the indirect losses, which will be further considered in Task 5.

Treatment of Losses. The treatment and measurement of air leakage and other losses in duct work is complex. Accurate measurements are more difficult to obtain for air flow than for water flow. Also, the duct work is part of an active system that includes the whole building: many air flows into and out of the various building spaces must be measured in order to determine the true losses, including system losses.

In this section a formalism for the treatment of duct losses is developed. This has threefold value:

1. It provides precise definitions of the various loss terms.
2. It provides a format for reporting experimental results.
3. It provides a framework for theoretical calculations.

Treatment of the duct loss problem, in particular of air leakage in ducts, begins with definitions of air flows. Figure 8 shows a house with a single conditioned zone (1) and a single unconditioned zone (2), both communicating with the outside ambient (0) and with each other. Return duct work (3) leads room air from the conditioned space to the furnace (4) and thence to the supply duct work (5). Duct work and furnace are assumed to be located in the unconditioned space.

The relevant air flows are represented by arrows in Figure 8. Both infiltration and exfiltration flows coupling the two building spaces and the outdoor ambient are represented. Supply and return air flows, duct air leakage, and air leakage out of (or into) the furnace itself complete the picture. These air flows are defined as follows:

F_{01} Infiltration from outside to conditioned space
F_{02} Infiltration from outside to unconditioned space
F_{10} Exfiltration from conditioned space to outside
F_{12} Air movement from conditioned space to unconditioned space
F_{13} Return air flow from conditioned space to duct
F_{20} Exfiltration from unconditioned space to outside
F_{21} Air movement from unconditioned space to conditioned space
F_{23} Air leakage from unconditioned space into return duct
F_{34} Return air flow into furnace
F_{42} Air leakage from furnace

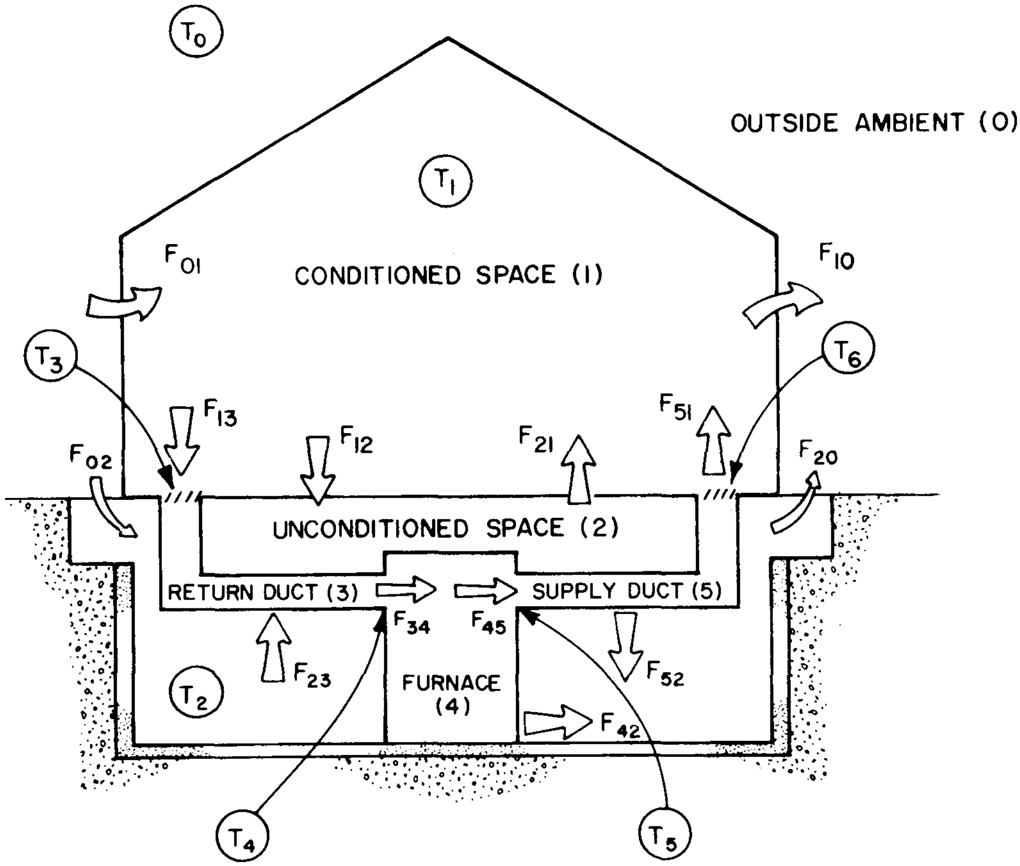

Figure 8. House and duct air flows.

F_{45} Supply air flow from furnace

F_{51} Supply air flow from duct to conditioned space

F_{52} Air leakage from supply duct into unconditioned space

Note that F_{51} and F_{13} include all direct air flows between the duct work and the conditioned space. These are not necessarily confined to register air flows: sometimes unauthorized flow paths accommodate a significant percentage of the air movement between the duct work and the conditioned space.

Six mass-balance equations can be written to link the 13 quantities defined above, on each of the six defined spaces:

$$F_{10} + F_{20} - F_{01} - F_{02} = 0,$$
$$F_{01} - F_{10} + F_{21} - F_{12} + F_{51} - F_{13} = 0,$$
$$F_{02} - F_{20} + F_{12} - F_{21} - F_{23} + F_{42} + F_{52} = 0,$$
$$F_{13} + F_{23} - F_{34} = 0,$$
$$F_{34} - F_{45} - F_{42} = 0,$$
$$F_{45} - F_{51} - F_{52} = 0. \quad (1)$$

Since any five can be added to yield the sixth, there are five independent equations and, therefore, 13 - 5 = 8 independent air flows.

Six temperature are also defined, as shown in Figure 8. T_0, T_1, and T_2 are the mean bulk air temperatures in the three major spaces. T_3 through T_6 are the air temperatures in the duct at the points indicated (entering the return duct, the furnace, the supply duct, and the conditioned space, respectively).

Next, the energy quantities of interest are defined. The first, Q_0, is the fuel input rate to the furnace, as measured by a fuel flow meter and converted to Btu/hr. The second is the heat delivered by the furnace, defined as

$$Q_F = C_V F_{45} (T_5 - T_4) , \qquad (2)$$

where C_v is the volume specific heat of air (0.018 Btu/ft^3-F at 70°F). Q_F is defined in this way, rather than via a strict mass/energy balance including F_{42}, to avoid giving the furnace credit for colder air pulled in from the unconditioned space (if F_{42} is negative) or unduly penalizing it beyond the loss of F_{42} not included in F_{45} (if F_{42} is positive). The furnace should be tight; if it is not, it should not get credit for air pulled in at a lower temperature.

The furnace efficiency η_F is then defined as

$$\eta_F = Q_F/Q_0 . \qquad (3)$$

The heat delivered by the duct is defined in a manner similar to that used for the furnace:

$$Q_D = C_V F_{51} (T_6 - T_3) . \qquad (4)$$

This definition emphasizes the duct work itself. Like the furnace, the duct work should be tight; if it is not, it should not get credit for air pulled in from the unconditioned space at lower temperature.

An alternative definition, taking infiltration effects into account, starts with Q_D but subtracts the effect of increased infiltration caused by system operation. If F_{01}', F_{10}', F_{02}', and F_{20}' are the infiltration rates between the building spaces and the outside <u>when the heating system is off</u>, then a net heat delivered by the duct work Q_N is defined as

$$Q_N = C_V [F_{51} (T_6 - T_3) - (F_{10} - F_{10}') T_1 + (F_{01} - F_{01}') T_0 - (F_{20} - F_{20}') T_2 + (F_{02} - F_{02}') T_0] . \qquad (5)$$

The four loss terms defined previously can now be quantified: (I) direct losses due to (A) duct leakage and (B) duct heat transfer, and (II) indirect losses due to effects of (A) infiltration and (B) furnace efficiency.

The direct losses Q_I are defined as the difference between the furnace delivered heat and the duct delivered heat:

$$Q_I = Q_F - Q_D . \qquad (6)$$

The duct leakage losses Q_{IA} are defined in terms of F_{52} and F_{23}:

$$\begin{aligned} Q_{IA} &= C_V\, F_{52}[(T_5 + T_6)/2 - T_2] + C_V\, F_{23}\, [(T_3 + T_4)/2 - T_2] \\ &= \frac{1}{2}\, C_V\, [F_{52}\, (T_5 + T_6 - 2T_2) + F_{23}\, (T_3 + T_4 - 2T_2)] \;. \end{aligned} \tag{7}$$

Here the average duct temperature is used to assess the loss in each duct. Some error could result from leakage occurring preferentially near the beginning or the end of the duct.

The duct heat transfer loss Q_{IB} is defined as the residual of the above two terms:

$$Q_{IB} = Q_I - Q_{IA} \;. \tag{8}$$

Presumably this term could be estimated independently from duct geometry and R-values, to provide a closure test.

The infiltration loss is the difference between the duct delivered heat and the net duct heat:

$$Q_{IIA} = Q_D - Q_N \;. \tag{9}$$

Finally, the loss due to furnace efficiency effects would be defined in terms of the furnace delivered heat *in situ* and the furnace delivered heat measured with a short, wide duct system having essentially no pressure drop.

An Example. To show how these concepts are used in practice, calculations are made for a 1500-ft^2 house with air infiltration from the outside of $\sim$1/2 air change per hour to both the conditioned and unconditioned spaces and air flow between the two spaces. The furnace air delivery rate is 1000 cfm, and the measured steady-state efficiency under standard test conditions is 78%. Assumption of a mean basement depth of 8 ft and a mean conditioned-space depth of 16 ft, leads to the primed flow rates on the left side of Table 3. When the furnace comes on, the following effects are assumed to occur:

1. 10% of the air delivered by the furnace is lost through the supply ducts (F_{45} = 1000, F_{52} = 100).
2. Exfiltration from the conditioned space increases by 50%, but infiltration is unchanged (F_{10} = 300, F_{01} = 200).
3. Exfiltration from the unconditioned space drops and infiltration rises, to compensate for the opposite imbalance in the conditioned space.
4. Infiltration into the return duct and the furnace (F_{23} = 150, F_{42} = -50) is met by exfiltration from the supply duct called out in (1) above and the unconditioned-space imbalance called out in (3).
5. Air flows between the spaces remain the same as before.

These assumptions, plus the mass-balances given by Eq. (1), define all the flow rates, which are listed in the middle of Table 3. Also assumed are the temperatures given at the right of Table 3.

The fuel input rate to this furnace is taken as 130,000 Btu/hr, and the steady-state efficiency measured with low-pressure-drop duct sections as 78%.

The return duct work is uninsulated, with a total area of 100 ft^2 and an effective R-value of 1.0°F-hr-ft^2-Btu. The supply duct work is also uninsulated (R = 1) and also has 100 ft^2 overall effective area.

Table 3
Flow Rates and Temperatures for Example Calculations

System-off flow rates (cfm)	System-on flow rates (cfm)	Temperature (F)
$F_{01}' = 200$	$F_{01} = 200$	$T_0 = 30$
$F_{02}' = 100$	$F_{02} = 150$	$T_1 = 70$
$F_{10}' = 200$	$F_{10} = 300$	$T_2 = 48$
$F_{12}' = 100$	$F_{12} = 100$	$T_3 = 65$
	$F_{13} = 800$	$T_4 = 60$
$F_{20}' = 100$	$F_{20} = 50$	$T_5 = 150$
$F_{21}' = 100$	$F_{21} = 100$	$T_6 = 140$
	$F_{23} = 150$	
	$F_{34} = 950$	
	$F_{42} = -50$	
	$F_{45} = 1000$	
	$F_{51} = 900$	
	$F_{52} = 100$	

On the basis of these hypothetical conditions, the energy quantities of interest are calculated. With $C_V = 0.018$ Btu/ft^3-°F, all flow rates are converted to ft^3/hr, to give heat rates in Btu/hr.

The furnace delivered heat is

$$Q_F = (0.018)\ (60)\ (1000)\ (150 - 60) = 97{,}200 \text{ Btu/hr.}$$

Since the measured steady-state efficiency is 78%, the furnace delivered heat for low-pressure-drop ducts is (130,000) (0.78) = 101,400 Btu/hr. Therefore, the losses due to furnace efficiency effects are 101,400 - 97,200 = 4200 Btu/hr.

The duct delivered heat is

$$Q_D = (0.018)\ (60)\ (900)\ (140 - 65) = 72{,}900 \text{ Btu/hr}$$

The direct losses equal

$$Q_F - Q_D = 97{,}200 - 72{,}900 = 24{,}300 \text{ Btu/hr.}$$

The duct leakage loss component is calculated from Eq. (7) as

$$Q_{IA} = (0.5)\ (0.018)\ (60)\ [100\ (150 + 140 - 2 \cdot 48) + 150\ (65 + 60 - 2 \cdot 48)] = 12{,}820 \text{ Btu/hr.}$$

Therefore the duct heat transfer loss Q_{IB} is 24,300 - 12,820 = 11,480 Btu/hr.

Direct computation of the duct heat transfer losses from duct areas and effective R-values, yields

$$\text{Supply} \qquad Q_{LOSS} = \frac{100\ \text{ft}^2\ (\frac{140 + 150}{2} - 48)^\circ\text{F}}{1.0^\circ\text{F-ft}^2\text{-hr/Btu}} = 9{,}700\ \text{Btu/hr;}$$

$$\text{Return} \qquad Q_{LOSS} = \frac{100\ \text{ft}^2\ (\frac{65 + 60}{2} - 48)^\circ\text{F}}{1.0^\circ\text{F-ft}^2\text{-hr/Btu}} = 1{,}450\ \text{Btu/hr;}$$

$$\text{Total} \qquad Q_{LOSS} = 11{,}150\ \text{Btu/hr.}$$

In a real situation, a closure this good (11,480 vs. 11,150 Btu/hr) would be considered remarkable!

Finally, the net duct heat Q_N is computed from Eq. (5) as

$$Q_N = (0.018)\ (60)\ [900\ (140 - 65) - (300\text{-}200)\ 70 + (200\text{-}200)\ 30$$

$$- (50 - 100)\ 48 + (150 - 100)\ 30]$$

$$= 69{,}560\ \text{Btu/hr.}$$

The infiltration loss is therefore $Q_N - Q_D$ = 72,900 - 69,560 = 3,340 Btu/hr.

The energy quantities and loss factors are summarized in Table 4. Although the numbers themselves are meaningless (the data having been manufactured for illustrative purposes only) the table shows how real results can be organized.

Needed Refinements. The treatment described above has essential drawbacks that need to be corrected in future work:

1. The formalism does not take capacitative effects into account, and is therefore good only for steady-state conditions. A proper treatment of cycling conditions is needed.

2. The duct work is assumed to lie in the unconditioned space, with no direct thermal coupling to the conditioned space. This may pose a problem where ducts are located close to a basement ceiling, with consequent direct heat transfer as well as possible infiltration from the supply duct to the conditioned space.

3. Direct heat losses from ducts located in an exterior wall are not treated.

Table 4
Results of Hypothetical Calculation of Duct Losses
NOTE: DATA ARE ILLUSTRATIVE ONLY. DO NOT USE THESE RESULTS.

Energy quantity	Value (Btu/hr)	Loss term	Value (Btu/hr)	Percent of input	
Fuel input	130,000			100	
		Stack and jacket loss	28,600		22
Steady-state heat (standard test)	101,400			78	
		Furnace efficiency effect	4,200		3
Furnace delivered heat	97,200			75	
		Duct leakage	12,820		10
		Duct heat transfer	11,480		9
Duct delivered heat	72,900			56	
		Infiltration effect	3,340		2.5
Net duct heat	69,560			53.5	

Subtask 1D. Reassess Energy Savings Potential

A preliminary assessment of the potential for energy savings by reduction of losses in residential forced-air systems was based on a projected 12% across-the-board improvement, derived from experimental data from a number of sources. This reassessment will use information obtained as described above on (a) better estimates of overall loss magnitudes, (b) relative importance of various loss mechanisms, and (c) relative frequencies of housing and duct-system types in each climate zone.

Better estimates of overall loss magnitudes will be obtained from several past studies and from ongoing work in the ASHRAE SP-43 project. Data on existing housing and new construction will be obtained as described in Task 2. The loss mechanism determination of Task 3 will be applied to each housing type/climate combination as appropriate to arrive at a refined estimate of losses due to each of the primary mechanisms.

This task will organize these data in a manner appropriate for a national loss reduction assessment. A scheme for assessing losses will be developed, with categories based on housing characteristics, duct placement, and climate. Development of the categories will be consistent with ability to estimate accurately enough the number of units in each.

The information so obtained will be used as a basis for estimating feasible percentage loss reductions. Reasonable assumptions will be made concerning possible advances in the state of the art that can be applied to loss reduction. From the number of units in each category, and the loss reduction potential per unit, the total loss-reduction potential can be estimated. The overall methodology is illustrated in Figure 9.

Disaggregation of the matrix-element approach will be utilized to pinpoint particular types of retrofit and new construction options that appear most applicable in the most significant space-conditioning climates, and hence would have the greatest national energy impact.

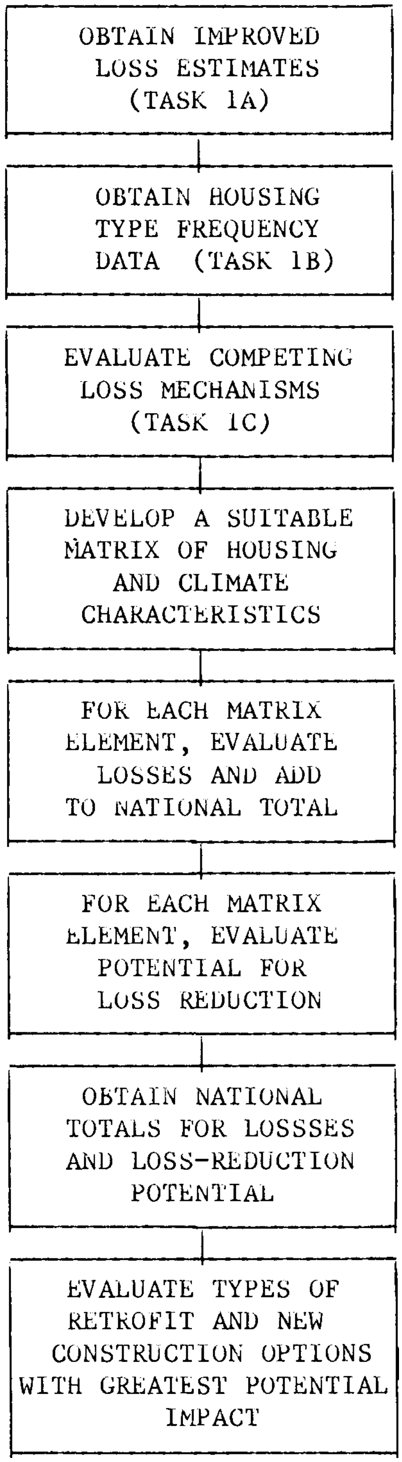

Figure 9. Methodology for estimating energy savings possible from reduction of duct losses.

Subtask 1E. Formulate Potential Solutions for Retrofit, New Construction, and Diagnostics

As planned, only a small effort has been put into this activity to date. Other task activities discussed above will be used to formulate a list of possible solutions to reduce significantly the energy losses in residential ducting systems. This list will also include concepts for diagnostic tools to be used in retrofit or new construction projects involving ducting systems, which will aid in the proper installation of these systems to provide maximized energy efficiency in their operation.

The list of possible solutions and concepts for diagnostic tools will be reviewed and analyzed by project staff, consultants, and industry representatives, using a qualitative systems analysis technique. In this technique, a comparative rating method is used to evaluate potential for energy savings, potential for application problems, and developmental risk. The results will be combined with the analysis of institutional economic, environmental, and health issues in Task 6 to establish priorities among potential solutions and needed diagnostic tools, which will then become part of the detailed research plan dealing with the reduction of losses in residential HVAC ducting systems.

Table 5 is a preliminary listing of technology-related factors that will be included in the systems analysis of various concepts for future research and development activities. Table 6 shows a set of evaluation criteria for each of the factors to be used in the systems analysis. The individual factors may be weighted when combining the totals to account for the relative importance of each factor. The systems analysis process will be reviewed by project staff and consultants prior to its use in rating solutions and concepts for the reduction of energy losses in ducting systems.

Table 5
Factors Considered for Inclusion in Analysis of Proposed Activities on Loss Reduction in Forced-Air HVAC Distribution Systems

<u>Energy Savings Potential</u>

- Direct surface losses from ducts
- Air leakage from ducts
- Induced infiltration to living space
- Furnace efficiency effect
- Embodied energy

<u>System Dependability</u>

- Materials performance degradation
- Expected service life

<u>System Feasibility</u>

- Ease of installation
- Sizing and specification problems
- Need to develop new materials

Table 6
Definitions of Criteria for Evaluating Technical Issues

DIRECT SURFACE HEAT LOSSES FROM DUCTS

DEFINITION: Losses attributable to heat transfer through duct walls into unheated space.

SCORE: +1 for each percent of expected reduction in fuel use attributable to direct surface losses (minus score if an increase is anticipated for this effect).

AIR LEAKAGE FROM DUCTS

DEFINITION: Losses attributable to leakage of air through duct joints, seams, or dampers into unheated space.

SCORE: +1 for each percent of expected reduction in fuel use attributable to air leakage in ducts (minus score if an increase is anticipated for this effect).

INDUCED INFILTRATION TO LIVING SPACE

DEFINITION: Losses attributable to increased air infiltration to building from outside ambient caused by operation of forced-air system.

SCORE: +1 for each percent of expected reduction in fuel use attributable to air infiltration (minus score if an increase is anticipated for this effect).

FURNACE EFFICIENCY IMPACT

DEFINITION: Losses attributable to reduced furnace efficiency caused by duct system design.

SCORE: +1 for each percent of expected reduction in fuel use attributable to furnace-efficiency effects (minus score if an increase is anticipated for this effect).

EMBODIED ENERGY

DEFINITION: Energy required to manufacture, market, and install the system.

SCORE: +1 for each 5% of expected reduction in embodied energy (minus score if an increase is anticipated for this effect).

MATERIALS PERFORMANCE DEGRADATION

DEFINITION: Defines degree and rate of degradation of materials that affect system performance.

SCORE:
- +2: Much less than for standard materials.
- +1: Moderately less than for standard materials.
- 0: About the same as for standard materials.
- -1: Somewhat greater than for standard materials.
- -2: Much greater than for standard materials.

Table 6
Continued

EXPECTED SERVICE LIFE

DEFINITION: Defines service life expected for the preposed solution, relative to current systems.

SCORE: +2: At least 30% greater than that of current systems.
+1: 10% to 30% greater than that of current systems.
0: About the same as for current systems.
-1: 10% to 30% less than that of current systems.
-2: Less than 70% of that for current systems.

EASE OF INSTALLATION

DEFINITION: Expresses the degree to which installation may be impeded for new construction or retrofit applications.

SCORE: +2: Installation easier than current practice for both new construction and retrofit.
+1: Easier than current practice for either new construction or retrofit, but not both.
0: About as easy as current practice for both new construction and retrofit.
-1: More difficult than current practice for either new construction or retrofit, but not both.
-2: More difficult than current practice for both new construction and retrofit.

SIZING AND SPECIFICATION PROBLEMS

DEFINITION: Denotes the degree to which the specification of the proposed solution in specific instances, or determining component sizes, will be a technical (computation) problem. Includes need for new design guidelines.

SCORE: +2: Sizing and specification will be considerably easier than for current systems.
+1: Will be somewhat easier.
0: Will be of about the same difficulty.
-1: Will somewhat more difficult.
-2: Will be considerably more difficult.

NEED TO DEVELOP NEW MATERIALS

DEFINITION: Expresses the degree to which the solution requires materials that are not readily available from industry.

SCORE: +2: All required materials are readily available from sources familiar to the HVAC industry.
+1: All required materials are readily available, but some may have to be obtained from nontraditional sources.
0: Some specialty materials may be required, but no new base materials need to be developed.
-1: New formulations of existing base materials will be required.
-2: New base materials will be needed with properties unavailable in existing polymers, metals, or other materials.

The following rationale was used to obtain a relative weighting factor for embodied energy compared with annual fuel energy use. In 1983, the annual primary energy use in the U.S. was 72 quads or 72×10^{15} Btu. The U.S. Gross National Product in that year was $\$3.3 \times 10^{12}$. Thus, on average, every dollar of value added to the economy entailed the expenditure of 22,000 Btu. A baseline price of $5,000 for an installed heating system, including duct work, gives an estimated $22,000 \times 5,000 \approx 100,000,000$ Btu of embodied energy. This is approximately equal to an average year's energy use for space heating in northern U.S. climates. The relative weighting of embodied energy vs. annual fuel energy then depends on the selection of an appropriate time horizon. The tentative choice is 5 years, which means that embodied energy will be accorded 1/5 the weight of annual fuel energy.

Subtask 1F. Assess Institutional, Economic, Environmental, and Health Issues

A formal screening process has been set up for use in judging the potential solutions developed in subtask 1E in terms of the indirect issues and barriers that could prevent or impede their application. This process will ensure that each proposed technical solution, however specific or generic, will be discussed and evaluated with respect to each of the pertinent issues, which are the following:

I. Institutional: A. Building costs; B. Variation from industry practice.
II. Economic: A. Consumer cost vs. benefit; B. Producer economics.
III. Environmental and Health: A. Emissions; B. Indoor air quality C. Safety.
IV. User Convenience: A. Noise; B. Frequency of service/repair.

For each potential solution, a judgment will be made about the expected difficulties due to each issue, and also about the potential for ameliorating them through design changes or R&D.

Each issue will be assigned a ranking from −2 to +2. Negative rankings indicate a barrier to implementation of the option, and positive rankings indicate a natural incentive (see Table 7). A typical forced-air system as commonly installed today will be used as the baseline for comparison.

Subtask 1G. Prepare a Research Plan for Residential Forced-Air Loss Reduction

The results of the six subtasks described above will be used as a data base in preparing a plan for long-term research on reducing losses in distribution systems. A group of collaborators will be assembled to work with BNL personnel on a continuing basis to critique the information gathered in the six subtasks, evaluate the need for further research, and prepare a comprehensive plan for future research.

Although this research plan cannot be anticipated in more than general terms at present, it is expected to encompass a period of five to ten years, and to relate specific projects to goals for loss reduction, and also related different project areas to each other. Specific milestones will be defined that will comprise an identifiable body of achievements.

The research is expected to be in the following general areas:

- Develop new materials and techniques for retrofit application.
- Develop new materials and techniques for new construction.
- Test materials and techniques.

Table 7
Definitions of Criteria for Evaluating Non-Technical Issues

BUILDING CODES		
DEFINITION:		Denotes the degree to which the proposed solution is compatible with existing building codes.
SCORE:	+2:	Completely compatible with all existing codes.
	+1:	Compatible with most local codes and all national codes.
	0:	Compatible with all national codes, but significant difficulties with local code variations are anticipated.
	-1:	Moderately at variance with one or more of the three major national codes.
	-2:	Significantly at variance with one or more of the three major national codes.
VARIATIONS FROM INDUSTRY PRACTICE		
DEFINITION:		Expresses the degree to which the proposed solution is compatible with industry practice in the areas of production, labor, marketing, installation, and service.
SCORE:	+2:	Proposed solution enhances the viability of current industry practice.
	+1:	Compatible with current industry practice in all 5 areas.
	0:	Compatible with current industry practice in 3 or 4 areas, but will experience moderate difficulty in 1 or 2.
	-1:	Will experience difficulty with current industry practice in 3 or more areas, but is not irreconcilable in any area.
	-2:	Fundamentally incompatible with current industry practice in one or more of the defined areas.
CONSUMER COST VS. BENEFIT		
DEFINITION:		Present value of life-cycle costs vs. life-cycle benefits over a given life cycle with no assumed salvage value.
SCORE:	+2:	Benefits exceed costs over a 3-year life cycle.
	+1:	Benefits exceed costs over a 5-year, but not a 3-year life cycle.
	0:	Benefits exceed costs over a 10-year, but not a 5-year life cycle.
	-1:	Costs are about equal to benefits over a 10-year life cycle.
	-2:	Costs exceed benefits over any reasonable life cycle.
PRODUCER ECONOMICS		
DEFINITION:		Cost and risk to a potential producer of getting into the business of manufacturing and marketing the proposed solution.
SCORE:	+2:	Proposed solution requires essentially no capital outlay.
	+1:	Requires modest capital outlay, low risks.
	0:	Requires modest capital outlay, moderate risks.
	-1:	Requires modest capital outlay, high risks.
	-2:	Requires high capital outlay.

Table 7
Continued

EMISSIONS		
DEFINITION:		Reflects the total level of emissions to the environment involved with the manufacture, sale, installation, and use of the proposed solution.
SCORE:	+2:	Proposed solution would result in greatly reduced emissions.
	-1:	Would result in moderately reduced emissions.
	0:	Would result in essentially unchanged emissions.
	-1:	Would result in moderately increased emissions.
	-2:	Would result in greatly increased emissions.
INDOOR AIR QUALITY		
DEFINITION:		Defines the level of pollutants to be found indoors, compared with a standard system with 0.5 air changes per hour.
SCORE:	+2	Very much lower indoor pollution levels.
	+1:	Moderately lower.
	0:	Essentially unchanged.
	-1:	Moderately higher.
	-2:	Very much higher.
SAFETY		
DEFINITION:		Identifies potential for fire and accident inherent in the implementation of the proposed solution.
SCORE:	+2:	Very much reduced safety hazards.
	+1:	Moderate hazard reduction.
	0:	Essentially unchanged hazard potential.
	-1:	Moderate increase in hazards.
	-2:	Very much increased hazard potential.
NOISE		
DEFINITION:		Level of audible sound level emanating from duct work or associated hardware, as experienced within living space.
SCORE:	+2	Greatly reduced noise.
	+1:	Somewhat reduced noise.
	0:	Noise essentially unchanged.
	-1:	Somewhat increased noise.
	-2:	Greatly increased noise.
FREQUENCY OF SERVICE/REPAIR		
DEFINITION:		Number of scheduled or unscheduled visits by service or repair personnel expected to be required during a given time period.
SCORE:	+2:	Greatly reduced frequency of service/repair.
	+1:	Moderately reduced frequency.
	0:	Essentially the same frequency.
	-1:	Moderately increased frequency.
	-2:	Greatly increased frequency.

- o Develop design guidelines for residential forced-air systems.
- o Develop low-cost diagnostic tools to quantify losses in duct systems.

TASK 2. ZONING IN RESIDENCES WITH FORCED-AIR DISTRIBUTION SYSTEMS

Subtask 2A. Technology Evaluation and Literature Search

Previous work on residential forced air zoning can be categorized as (a) evaluation of energy savings due to zoning, (b) modeling and computing zone loads and airflow between zones, and (c) development of measurement techniques to determine interzonal interactions.

Moyers and Nephew [18] evaluate the potential energy savings due to temporal and spatial zoning in residential buildings. They compare six lifestyles and conclude that the use of variable capacity HVAC systems having controlled distribution and temperature setback capability can, with relatively minor changes in lifestyle, produce annual savings of more than 1.5 quads, nationally. They use a computer simulation of heat pump performance to calculate energy use.

Walton [19, 20, 21, and 22] presents models of zone loads and interzonal interactions. With a computer program using a heat-balance method of determining zone loads [19] he runs test cases and compares them with the NBSLD model results, but draws no conclusions about building performance. He presents a model [20] for computing the infiltration and airflow between rooms in a loads-predicting computer program, and he calculates airflows, room temperatures, and heating loads for a typical townhouse under different conditions. The results indicate that, when the interroom openings in a house are large compared with the envelope openings (typical in residential construction), the infiltration and total load can be accurately calculated by assuming no resistance to airflow between rooms. This model is applicable to high and low openings in a single wall, but it does not address doorways where bidirectional flow can occur, or airflows through openings in floors as affected by thermal stratification. Large amounts of air will be exchanged if a warm room is below a cold one, especially if two openings set up a large convection pattern. Walton eliminates some of these model deficiencies [21] by adding the ability to model two-way flow through large openings by considering density differences due to temperature differences in adjoining rooms. This new model is incorporated into a complete load determination program, the Thermal Analysis Research Program (TARP). The overall objective in developing TARP is to provide a comprehensive modeling technique for predicting simultaneous transfer of air, moisture, and heat in and through multiroom buildings.

Walton discusses [22] the latest developments in the heat balance method for simulating room thermal response, most of which have been incorporated into TARP. Response factors are used to analyze one-dimensional conduction. Models have been designed for convective exchange between rooms, although room convection coefficients are still uncertain. Walton concludes that further study is needed on the simulation of room air stratification both for its direct effects on comfort and energy requirements and for its effect on interroom air movement. Validation of the TARP model is needed, as well as data on air openings data for typical construction components.

Dietz [23, 24] describes techniques for measuring interzonal interactions and air movement. The use of perfluorocarbon tracers (PFT) allows determination of airflow rates in up to four zones at one time. Results of measuring air movements between zones are presented for a jailhouse and for a quadruplex housing unit. These techniques can be used to determine the extent of interzonal interactions and to validate multizone load models.

Subtask 2B. Study Interzonal Interactions

This area of work deals with the (generally unintended) transfer of heat and/or humidity between zones of a building. Such transfer reduces or limits the effectiveness of zoning, whose purpose is to maintain temperature and humidity differences between various subspaces of a building in order to conserve energy.

The assessment and planning activities undertaken during FY 85 will be in the following categories:

1. Literature search for previous work on interzonal interactions. This is discussed under subtask 2A.

2. First-order calculations and modeling. Calculations and modeling ranging from pencil and paper figuring to simple computer techniques will be used to get preliminary answers to generic questions such as whether insulation between zones is necessary or helpful, and to what extent open doors between zones lessen the interzonal temperature gradient.

3. Simple experiments that can be done in a few hours to a few days with simple portable instrumentation, and require a moderate analysis effort. Homes of BNL employees will be used to obtain order-of-magnitude estimates of gross effects such as maintainable temperature differences across zone boundaries and time constants for relaxation of temperature differences.

4. Plans for needed future work more extensive than what can be accomplished in this subtask. Such work would become part of the overall research plan to be developed in subtask 2F.

Insulation. To the question of whether insulation is needed in partitions that separate zones, the answer seems in general to be negative. In a zoning study [25] in connection with hydronic systems, a partition wall of standard construction was calculated to have an R-value of 3.45°F-hr-ft^2/Btu uninsulated and 12.05°F-hr-ft^2/Btu insulated. The former performed nearly as well as the latter in maintaining zoning benefit. The reason is that the heat flowing through an interzonal partition does not necessarily detract from the interzonal temperature difference. If the exterior temperature is low enough to cause a need for heat in the cool zone, that heat can just as well come through the warm/cool zone partition as from the space heating system. Heat is actually lost only when the exterior temperature is high enough to cause the additional heat coming through the partition to raise the cool zone temperature above that intended.

A bin-type calculation of the impact of partition insulation was done for Kansas City. Two levels of envelope thermal integrity were studied, represented by whole-house UA values of 800 and 400 Btu/hr-°F. The former is fairly typical of existing housing, and the latter represents good (but not extraordinary or superinsulated) current practice [26]. This UA was assumed to be equally divided between the warm and the cool zones. The insulated and uninsulated partitions were assumed to have R-values of 12.5 and 3.125°F-hr-ft^2/Btu, respectively; this provided a factor-of-four ratio, and the values were within computational tolerances of the computed ASHRAE values referred to above.

Calculations were made for two different partitions: a 250-ft^2 (about 8 x 30 ft) vertical partition between two zones in a single-story house, and a 1000-ft^2 ceiling between the first and second floors of a two-story house with 2000 ft^2 living space. The cool zone was maintained at either the zone set-point temperature (50°F) or the lowest temperature attained with no heat input to the zone, whichever was lower.

The results (Table 8) show that, for either envelope quality, the incremental energy savings due to insulating the partition are 1.3 million Btu for the 250-ft^2 partition or 5.4 million Btu for the 1000-ft^2 partition; that is, about 5300 Btu per square foot of partition. If a cost of $10 per million Btu is assumed for delivered space heating energy, and an 8-year payback is required, the allowed cost per square foot to insulate the partition is $0.42. Since it seems unlikely that the needed insulation can be installed at this price, the conclusion is that the interzone partition probably should not be insulated, and certainly not in retrofit situations.

Further work will be done to refine the assumptions used in computing the allowed cost, to check for errors, and to do calculations for more cities over a range of climates.

Convective Interchange. Portals of interzonal communication such as doorways, hallways, and stairwells have a marked effect on air movement and consequently on energy flow between zones. These effects will be investigated under four distinct sets of conditions:

Case A. All zones heated to the same temperature (unzoned condition).
Case B. Doors open between zones; heat into warm zone only.
Case C. Doors closed between zones; heat into warm zone only.
Case D. Doors closed between zones; both zones heated, but to unequal temperatures.

A methodology for these calculations has been developed which will use 5° temperature bins and the above boundary conditions. Several cities representing a range of climatic conditions will be studied.

Table 8
Effect of Zone-Partition Insulation on Energy Savings

Whole-house UA (Btu/hr-°F)	Interzonal partition			Annual heating load, unzoned (Btu x 10^6 Btu)	Energy saved via zoning* (Btu x 10^6 Btu)
	Type	Area (ft^2)	Insulated?		
400	Vert.	250	Yes	58.1	17.7
			No	58.1	16.4
	Horiz.	1000	Yes	58.1	16.4
			No	58.1	11.0
800	Vert.	250	Yes	116.3	35.8
			No	116.3	34.5
	Horiz.	1000	Yes	116.3	34.5
			No	116.3	29.0

*Subtract uninsulated value from insulated value to obtain increment due to insulation.

A considerable amount of related research has already been done, the results of which are being accumulated for study and evaluation. This evaluation will aid in the quantification of interzonal interactions and the identification of additional areas of research for the overall program plan. The areas of related research identified thus far include work done at the following research centers:

1. BNL - The application of perfluorocarbon tracers for multi-zone and flow measurements. Russell Dietz et al.
2. LNL - Natural convection air flow within buildings. Douglas Balcomb et al.
3. NBS - Modeling of air movement within buildings - TARP. George Walton et al.
   Design of smoke control for buildings (ASHRAE Design Manual). John Klote et al.

Subtask 2C. Assess Occupant Behavior

The effect of occupant behavior on energy use has been studied by psychologists and energy scientists. Psychological research on energy conservation has included behavioral and social-psychological approaches. The behavioral approaches to increasing conservation include providing (1) encouragement to conserve, (2) information on ways to conserve, (3) monetary incentives, and (4) information on recent energy consumption (feedback).

Encouragement and information on energy conservation have been most often provided by unsystematic campaigns by government or energy industry sources. The research shows that specific recommendations (e.g. "turn down thermostat") are more effective than general requests to conserve energy. Also, information as part of a broader program increases the adoption of energy saving practices or equipment.

Investments in energy conserving appliances or insulation may be made for financial reasons. The effects of initial cost, energy cost, and projected savings on consumer decision making are not clear. Research on feedback to consumers about rates of energy consumption has shown that frequent feedback (at least daily) is a highly effective means of reducing energy use in the home.

The social-psychological research is aimed at determing the effects on energy conservation of consumers' attitudes toward energy, the energy crisis, science and technology, and comfort and health. The results of such research can be used to increase use and acceptance of zoned distribution systems. They can also be helpful in designing controls and metering systems that enable consumers to conserve energy. The energy savings due to zoning of a heating and cooling distribution system depend largely on the day-to-day actions of those using the conditioned space. This means that decisions to conserve must be made frequently to accomplish energy savings. The motivation for such actions is different from that for those that need be performed only once to have the desired effect (e.g. adding insulation to the home). The installation of a zoneddistribution system will not conserve energy; those using the system must lower the thermostats in unoccupied spaces and keep doors shut between zones.

Subtask 2D. Determine National Energy Savings Potential from Zoning of Residences with Forced-Air Distribution Systems

A preliminary assessment of energy savings potential from zoning in residences with forced-air distribution systems was based on a projected 30% across-the-board improvement. This was derived from a study of heating and cooling of buildings with irregular occupancy patterns [5] and a study of zoning in residences [25]. This reassessment will use information obtained as described above on (a) better estimates of potential technology improvement, (b) relative frequency of generic housing types, (c) interzonal interactions, and (d) expected occupant behavior patterns.

Better estimates of potential technology improvement will be obtained from an analysis of developments found in various published sources. The data set on housing obtained in subtask 1B will be used here as well. The assessments of interzonal interactions and of occupant behavior performed in subtasks 2B and 2C will also be used. The methodology to be employed is outlined in Figure 10.

In this task area, the above information will be organized so that it can be used to assess the national energy savings potential from zoning of residences with forced-air distribution systems, with emphasis on occupant behavior and on the degree to which existing housing, not designed for zoning, could be zoned.

The disaggregation of the matrix-element approach will be taken advantage of to pinpoint particular retrofit and new construction options having the greatest applicability in the most significant space-conditioning climates, and hence the greatest national energy impact.

Subtask 2E. Identify Technical Approaches and Research Needs

As planned, only a small effort has been expended in this activity area to date. Results from subtasks 2A, 2B, and 2C are needed as input. These results, along with a survey of commercial zoning equipment and products, presented in a concise format, will provide the basis for developing potential technical approaches and identifying research needs for efficient zoning with residential air-distribution systems.

These concepts will be prioritized and included in a formal detailed research plan (subtask 2F) to be delivered at the end of the current fiscal year. The prioritization will be based on a review by project staff and consultants, and will be done by a systems analysis technique involving assessment of the potential for energy savings and of technical and non-technical issues, as shown in Table 9. These are the same generic issues considered in Task 1, but other, separate issues may arise as the work progresses.

A survey of the commercial air conditioning industry has been initiated, with regard to products and product specifications that may be applicable to the residential sector. This survey will be based on lists of manufacturers that make ducting and zoning products used with air handling equipment, taken from sources including the ASHRAE-Products Specification File (1982), the Air Conditioning Heating and Regrigeration News 1985 Directory, and the 84/85 HPAC Info-DEX published by Heating, Piping, and Air Conditioning Magazine.

Some effort has also been expended in planning and outlining an approach to the systems analysis of the various potential research areas, ideas, and concepts associated with residential forced-air zoning.

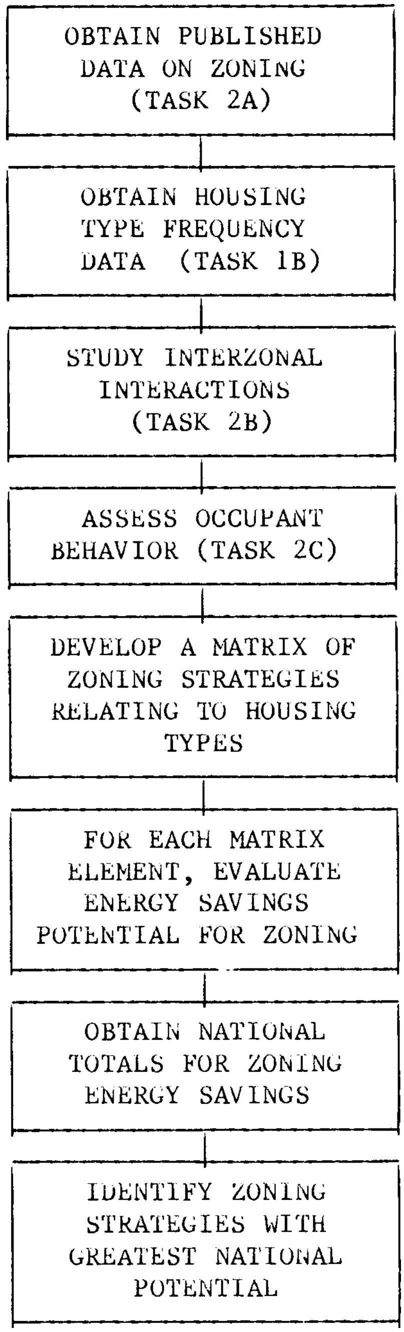

Figure 10. Methodology for estimating energy savings possible from zoning of residential forced-air systems.

Subtask 2F. Prepare a Research Plan for Residential Forced-Air Zoning

The results of the above five subtasks will be used as a data base in preparing a long-term research plan for zoning in residences with forced-air distibution systems. To prepare this plan, a group of collaborators will be

Table 9
Factors Considered for Inclusion in Analysis of Proposed Activities in Zoning of Residential Forced-Air HVAC Systems

Energy Savings Potential	Institutional Issues
o Reduction in envelope heat loss	o Building codes
o Infiltration effects	o Variations from industry practice
o Furnace efficiency impact	
o Embodied energy	Economic Issues
	o Consumer cost vs. benefit
System Dependability	o Producer economics
o Materials performance degradation	
o Expected service life	Environmental and Health Issues
	o Emissions
System Feasibility	o Indoor air quality
o Ease of installation	o Safety
o Sizing and specification problems	
o Need to develop new materials	User Convenience Issues
	o Noise
	o Frequency of service/repair

assembled to work with BNL personnel on a continuing basis to critique the information gathered in the five subtasks, evaluate the need for further research, and prepare a comprehensive plan for future research.

This research plan cannot be anticipated in more than general terms at present, but it is expected to encompass a period of from five to ten years, and to relate specific projects to goals for zoning, and also relate different project areas to each other. Specific milestones will be defined that will comprise an identifiable body of achievements.

The research is expected to be in the following general areas:

- o Develop control strategies for zoned residential forced-air heating and cooling systems.
- o Identify optimal hardware configurations for zoned residential forced-air heating and cooling systems.
- o Identify optimal central equipment configurations for zoned residential forced-air heating and cooling systems.
- o Develop guidelines for distribution system design and zone configuration.
- o Test optimized systems.

TASK 3. HYDRONIC SYSTEMS

Subtask 3A. Technology Evaluation and Literature Search

A start has been made in gathering recently reported findings and information dealing with the area of hydronic heating systems in residential buildings. The evaluation will be directed towards methods of improving the efficiency of hydronic distribution systems, including concepts related to convector heat transfer effectiveness, zoning strategies, controls, and the application of condensing heating plants on a retrofit basis. This work will form a base for further planning in this area. It will also provide an up-to-date base for comparison in analyzing the result of a survey of European practices and research in hydronic heating systems (subtask 3B).

A computer search has been done with the DOE-RECON information service using the Energy Data Base File and the Engineer Index (File 8), and DIALOG computer information service (Files 148 and 96), the Trade and Industry Index and the BHRA Fluid Engineering Abstract. The results are being analyzed with regard to the newer records and reports that were not reviewed as part of the activities in space conditioning technology during the last seven years. About ten new papers have been found that may be useful in the current project.

Subtask 3B. Evaluate European Research and Practice

In view of the extensive European experience with hydronic heating systems in residences, which are more common and more varied in design than those in the U.S., it was decided to engage an outside firm with experience and active contacts in the European HVAC market to survey the European systems to determine whether transfer of any of this technology to the U.S. would be beneficial in terms of energy savings.

A draft Notice of Program Opportunity describing the work has been prepared, as follows.

Survey of European Hydronic (Hot Water) Residential Heating Technology.

Conduct a three-month survey of European hydronic (hot water) residential heating technology for potential application to the United States hydronic heating industry. The survey will identify European research, findings, and practices used in providing high-efficiency hydronic heating systems for the residential sector. Particular attention will be placed on convector baseboard heat exchangers (effectiveness), distribution systems, zoning of the systems, heat loss reduction in the systems, and concepts or technology to improve central plant (oil, gas, or solid fuels) efficiency.

Organizations possessing special qualifications including the following should submit brief information, approximately two or three typewritten pages in length, within 15 days of this announcement: (1) In-depth technical knowledge of the United States residential hydronic heating industry and practices, (2) knowledge of current and prior European research, technology, and practices in residential hydronic heating systems, (3) availability to directly survey the European hydronic heating industry, foreign national research in this area, and private research and development currently underway in Europe, and (4) availability of qualified staff and facilities to perform the work.

Subtask 3C. Identify Problems and Energy Saving Potentials

Based on a review of the technological status of hydronic systems at the international level an evaluation will be made of new approaches to heating and cooling, losses and loss mechanisms, overall building energy effects, and human factors. Such concepts as continuous circulation, slab (radiant) heating and combined radiant and convective distribution systems are used widely overseas and need to be reconsidered.

Current understanding of loss mechanisms in U.S. hydronic systems. Most losses are due to poor installation practices rather than design or technical problems. The most common mistake is to install uninsulated or poorly insulated distribution system pipes outside the conditioned spaces, where losses are effectively irretrievable to the building system. In contemporary housing pipes are often placed as follows:

1. in crawl spaces and basements near foundation walls or infiltration paths;
2. in the lower extremity of the slab in contact with soil and moisture;
3. near slab edges exposed to near-ambient conditions;
4. with risers in exterior walls outside building insulation;
5. in second-story overhangs without insulation;
6. in below-grade garage walls and ceilings;
7. in attics above the building insulation;

Another mistake is to place baseboard convectors in thermal contact with exterior walls.

It is, in a way, easier to correct losses in hydronic systems than in forced-air ducts because of the small, leak-free surface areas of the pipe runs, which in most exposed cases can be completely wrapped with insulation. (As with forced-air systems, exterior wall distribution runs are difficult to insulate). The potential for hydronic distribution systems lies in the possibility that, through careful design and installation, they can be made to deliver heat to building spaces more efficiently than comparable forced-air systems.

In carrying out this subtask, because forced-air system installations greatly outnumber hydronic in the current U.S. market, energy savings opportunities will be sought in the following two areas:

1. Retrofit concepts that are cost-effective and feasible in a significant fraction of existing installations.
2. For new construction, hydronic system concepts that can save energy relative to the forced-air systems that are and probably will be their main competition.

Subtask 3D. Determine National Energy Savings Potential for Hydronic Systems

The technical possibilities for saving energy in hydronic systems, identified in preceding subtasks, will be evaluated in terms of their potential for energy saving on a national basis. Emphasis will be on retrofit options because of the much larger number of existing hydronic systems than of new installations, but the potential for new technology will also be evaluated vis-a-vis forced-air system options.

For retrofit, the primary areas for energy savings are the following:

1. Reduction of losses through walls from poorly-insulated baseboard heat exchangers, and through slab-installed systems.
2. Reduction of return-water temperature via reduced flow rate, resulting in improved boiler efficiency and opening the possibility for a type of zoning using an existing single loop.
3. Full zoning using split circulation loops.

The new construction evaluation will draw heavily on the European experience as elucidated in subtask 3B. The objective will be to determine the potential for the following:

1. Renewed interest in hydronic systems in the U.S.
2. Energy savings relative to standard forced-air systems.

Subtask 3E. Identify Research Topics

This area of work will identify research needs in the reduction of system losses or in the improvement of performance of the building/HVAC system. The results of subtasks 3A through 3D will be reviewed with emphasis on the development of generic concepts and on performance validation of hydronic systems and operational strategies as they are implemented in the field, rather than on equipment development. The results are expected to yield a group of research projects that will probably combine analytical computations with laboratory and/or field validation experiments.

Subtask 3F. Develop Recommended Research Plan for Hydronic Systems

Based on the results of the previous five subtasks, a research plan will be developed. This plan will rank research work on hydronic systems according to the criteria of energy savings potential and an evaluation of technical problems to determine research priorities for hydronic systems. The deliverable for this subtask will be a research plan which will include priorities and logic charts for work on hydronic systems. This subtask will not be started until the previous five are near completion.

TASK 4. RADIANT HEATING AND COOLING SYSTEMS

Subtask 4A. Technology Evaluation and Literature Search

Information on radiant heating and cooling systems, radiant effects on thermal comfort, and energy savings potential of radiant systems is being gathered and evaluated. Product literature is also being gathered to evaluate commercially available systems.

Several laboratories have done research on thermal comfort and radiant heat. Berglund [27], showed in comparison tests, that people will accept a space being cool upon entry if it can be brought quickly to a comfortable level with radiant heat. He also studied controls for radiant heating systems. A sensor that averaged the air and mean-radiant temperatures provided greater occupant comfort at reduced energy consumption than an air-temperature sensor. The average of air and mean-radiant temperatures is a good approximation to the operative temperature. The operative-temperature controller provided greater comfort by reducing overheating of occupants. The results of this study have energy saving applications for buildings with intermittent occupancy and for zoning.

Lebrun and Marret [28] studied the microclimate in a test room with radiant heating systems. They tested the effectiveness of radiant floor and ceiling panels by considering thermal comfort conditions as well as energy consumption. They compared radiant heating with warm-air heating and concluded that, for very bad insulation or large areas of single glazing, radiant heating is the most economical system, but warm-air heating provides more uniform comfort conditions and is therefore more comfortable. As insulation increases, the difference between heating systems is reduced, and warm-air heating becomes the most efficient with high levels of insulation. This study is, however, limited to steady-state conditions only.

The conditions under which radiant heating systems can save energy have not been determined. This potential savings has two causes: (1) radiant heating systems heat the body directly and thus maintain comfort at lower air temperatures than needed with convective heating systems, and (2) radiant heating systems are typically zone-controlled and therefore can be operated more efficiently than unzoned heating systems. The California Energy Commission has developed techniques for modeling radiant heating systems with existing computer programs. [29] They assume that the permissible air temperature depression with radiant heating system is 2°F, but this remains a subject of controversy. The increased heat loss due to higher surface temperatures is subtracted from the savings due to lower air temperature to obtain the amount of energy saved. This method does not consider zoning effects and has not been verified.

Commercially available (not custom designed) radiant heating systems are currently limited to electrically heated surface-mounted panels, typically comprising an electric-resistance ribbon encased in Mylar or asbestos and backed by insulation. They are heated to 150° to 200°F and are available in sizes ranging from 2 x 2 ft to 4 x 8 ft. Outputs range from 150 to 1640 watts. Producers include Aztech International of Albuquerque, NM, and TVI Energy Corporation of New Canaan, CT.

A typical custom-designed radiant heating system consists of pipes imbedded in the ceiling, walls, or floors of a home. A warm fluid (150° to 200°F) circulated in the pipes heats the surfaces of the room by conduction. The warmed surfaces heat the occupants and objects in the room by radiation.

Very little work on radiant cooling has been reported, on either systems design or thermal comfort. Land [30] did one experiment in a test cell with radiant paneling. He measured radiation losses from human subjects and also had them report their level of thermal comfort. He concluded that radiant cooling can provide satisfactory comfort, but he did not compare the energy use with that of a conventional cooling system.

Radiant cooling has been used in commercial buildings. For example, the passenger concourses of Chicago's O'Hare Airport have concealed radiant heating panels that are also used to meet a portion of the sensible cooling load in summer, estimated as a third of the total.

Subtask 4B. Assess the Potential of Radiant Systems

After the state of existing technology and the human factor requirements have been reviewed, a list of candidate radiant and hybrid-radiant systems with significant savings potential will be prepared and ranked in terms of practicality, safety, human factors, and potential savings.

The pursuit of this task depends on completion of the technology survey and subsequent review of the results. Some quantification of savings has been done, based on field experiments with radiant heating in specific applications. One experiment, carried out at the Rose-Hulman Institute of Technology, Terre Haute, Indiana, [31] over two years, involved two buildings, the Rotz Laboratory and the Black Gymnasium, both consisting of large spaces with high ceilings (16 ft and 30 ft, respectively) and normally heated with gas and electric forced-air systems, respectively. For the test, overhead radiant systems were operated alternately with the forced-air systems over half of each heating season. High-intensity gas-fired surface combustion units were used in the Rotz Laboratory, and an array of electric metal-sheath radiant heating units in the Black Gymnasium. The results indicated savings for the use of continuous heating radiant systems of about 13% for the Laboratory and 16% for the Gymnasium.

Previous analytical work done for BNL by Gard, Inc. [5] in the subject area of heating of buildings with irregular occupancy indicated potential savings of 13 to 60% for specific generic building types. The radiant systems considered were assumed to be used in transient pull-up applications designed for rapid achievement of a sensation of comfort upon occupant entry into spaces previously held at a deep temperature set-back. Table 10 summarizes the results.

Table 10
Comparison of Annual Heating Energy Requirements: 10°F Night Setback Versus Heating During Occupancy Only [5]

Space type	Annual heating energy requirements: 10°F night setback*	Annual heating energy requirements: Occupancy based heating**	Site energy savings: 10^6 Btu	Site energy savings: %
Single-family				
Minneapolis	165.1	124.9	40.2	24.3
Chicago	108.0	80.1	27.9	25.8
St. Louis	99.5	73.7	25.8	25.9
Low-rise apt.				
Minneapolis	39.7	34.1	5.6	14.1
Chicago	27.3	21.8	5.5	20.1
St. Louis	24.8	19.8	5.0	20.2
High Rise Apt.				
Minneapolis	39.0	33.8	5.2	13.3
Chicago	25.9	21.3	4.6	17.8
St. Louis	23.4	19.3	4.1	17.5
Classroom				
Minneapolis	89.9	56.1	33.8	37.6
Chicago	60.5	35.2	25.3	41.8
St. Louis	54.4	31.1	23.3	42.8
Auditorium (w/reheat)				
Minneapolis	205.1	110.2	94.9	46.3
Chicago	136.9	58.3	78.6	57.4
St. Louis	122.4	50.2	72.2	59.0
Auditorium (w/reheat)				
Minneapolis	160.9	91.4	69.5	43.2
Chicago	100.5	39.6	60.9	60.6
St. Louis	90.5	33.2	57.3	63.3

*Space maintained at 70°F during the day and 60°F at night.
**Temperature set back to 50°F during all unoccupied hours.

Subtask 4C. Identify Research Needs

Radiant system configurations with significant savings potential will be examined in detail and categorized in terms of implementation, refit versus new construction, and anticipated user acceptance. The results will be used as a base for developing a set of research needs. The results will include additions to the existing data base for the design and implementation of radiant systems.

Although the effort in this task area depends on the results issueing from previous tasks, the currently perceived areas of required research can be stated in general terms. These areas include but are not limited to the following:

1. Quantification of air temperature stratification effects of conventional versus radiant heating systems.
2. Thermal and radiant anomalies (radiant draft sensations) and their effects on occupants.
3. Asymmetric radiation: establish limits for this transfer mechanism for vertical and horizontal surfaces.
4. Spot heating and cooling: examine the feasibility of local heating or cooling of hands and feet as a substitute for whole-space conditioning.
5. Altered clothing materials to enhance desired radiant effects.
6. Field tests of room surface treatment materials for infrared radiant effects.
7. Laboratory or field tests to verify projected energy savings of treated and radiantly heated spaces.
8. Field tests of the impact of infrared radiant heating on comfort, including study of required infrared temperature, shadow effects, excessive radiant heat effects, shielding effects of clothing (compared with bare skin), and effects of drafts.

Technical support for this area of work is being sought from the research and industrial communities. A list of prospective consultants has been prepared and biographical information is being secured in preparation for the final selection of consultants and purchase of services.

Subtask 4D. Prepare a Research Plan for Radiant System Research

Formal activity under this subtask has not yet begun, but previous planning activity indicates that the major research needs will include measurement and correlation of heat transfer parameters; the integration of heating, cooling, and storage functions in a single system design; a study of control strategies (including zoning); investigation of means to balance sensible and latent cooling loads; and engineering evaluations of a prototype system design. The details of these areas discussed below, are tentative and are expected to be extensively modified in the final research plan. They are included here to illustrate the types of activities planned.

In order to measure and correlate heat transfer parameters, measurements of radiative and convective heat transfer coefficients of various systems will be made under conditions which would be encountered in actual heating and cooling applications. These measurements could be made in a small (10 x 10 ft) well-insulated room of modest design and construction. Overall heat transfer will be determined by measuring water-side temperature drops and flow rates (for hydronic systems) and energy input, and will be checked against room energy balances. Transient measurements will also be made to determine time constants of components and building spaces.

In integrating heating, cooling, and heat storage options into a system, a number of types of combustion equipment need to be considered. Some of these may involve condensing operation. Because of the possibility of a non-pressurized distribution system, a number of unconventional options will be possible. The following subtasks could be performed:

- o Evaluate conceptual system designs with focus on the primary heating equipment. The best means of providing domestic water heating and space cooling will be emphasized. Evaluation criteria will be technical feasibility, simplicity, and estimated cost advantage. Candidate designs showing the most promise will serve as models for further development.
- o Develop detailed designs of the combustor subsystem based on the specifications implied in the selected conceptual design(s). One or more prototypes will be fabricated and will be subjected to a series of performance evaluations intended to provide generic information concerning the expected performance of combustors in the intended application.
- o Develop detailed designs for the primary heat exchange/storage subsystem. The means for transferring combustion heat to the heat transport water used in the system, and for storing the heat between on-cycles of the combustor, will be detailed. Major differences between these designs and conventional boiler systems can arise if an unpressurized system is used. This can result in lower material requirements and high efficiency. Means for maximizing overall efficiency consistent with marketability will be the major goal.

Control strategies, including zoning, for heating and cooling will be investigated. These include on/off, temperature modulation, flow modulation, preprogrammed setbacks, and occupancy-based heating and cooling. Energy and thermal comfort implications of each strategy will be evaluated and compared. This task will be performed analytically rather than experimentally to permit the rapid evaluation of a large number of control options.

Another task activity will be to seek a means for balancing sensible and latent cooling loads. A major problem, especially in energy-efficient buildings, is the rising prominence of latent cooling loads relative to sensible loads. Radiant cooling makes possible at least two novel means of matching loads that are heavily weighted in the latent direction. The first is to provide thermal comfort at higher-than-normal room ambient temperatures by depressing the mean radiant temperature: at a higher room temperature, for a given absolute humidity, the relative humidity will be lower, thus facilitating evaporative heat loss from the skin and promoting comfort. The second possibility is to enclose the heat exchanger in a convoluted membrane that is permeable to water vapor but impermeable to air (e.g. Dupont's Tyvek). These and perhaps other schemes will be investigated analytically, and recommendations will be made for subsequent phases of the project.

The next phase of the program will involve a series of overall engineering evaluations of radiant systems. This subtask will be to detail the final designs and to construct the necessary hardware for the system experiments. The laboratory work will comprise two distinct phases, described below.

Engineering system development will emphasize the interactions that will take place throughout the system. The performance of entire systems will be measured under a set of conditions representing the totality of what is expected to be seen in practice. This will reveal aspects requiring appropriate engineering emphasis. Concurrently, progress will be continuously monitored to assess the degree to which the goal of reliable systems is being approached.

Engineering system evaluation will comprise long-term evaluation of the concept at a point of technical maturity such that design parameters are no longer being changed and sufficient reliability has been achieved for credibility within the industry. The output from this final subtask will be information and data for industry to proceed with product development and marketing activities appropriate for the private sector.

A preliminary schedule of these activities is presented in Figure 11. This will be updated, detailed, and articulated in the course of the work under this subtask.

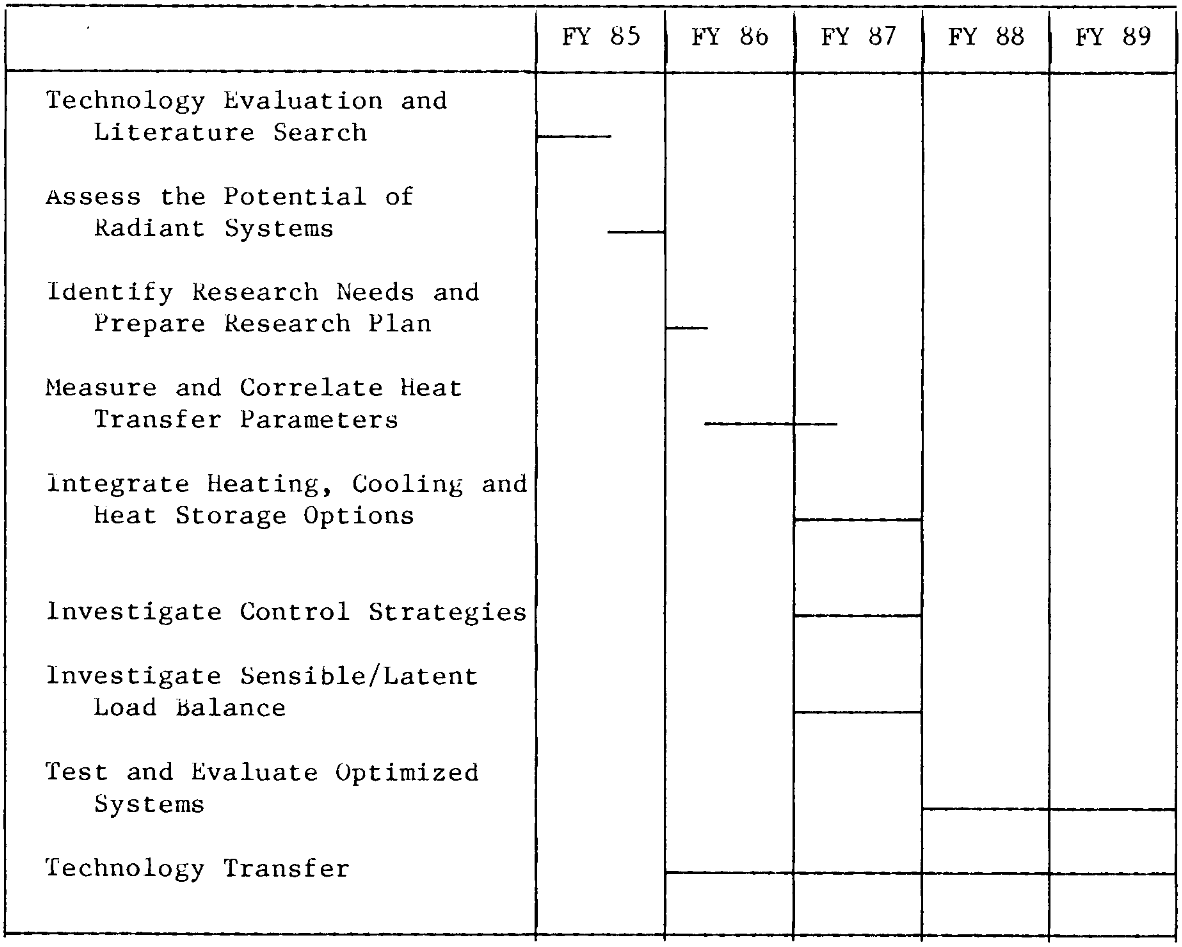

Figure 11. Tentative outline of a five-year plan for radiant heating and cooling research.

TASK 5. ASSESS NEED FOR SYSTEM INTEGRATION RESEARCH

The planned study of system integration deals with the interactions of building subsystems (the building envelope, occupied subspaces, and space conditioning equipment) that affect the distribution system and its performance in delivering heating or cooling to the points of utilization.

The work in this area is expected to draw heavily on the forthcoming results of other tasks within the program and on input from consultants in research and industrial sectors. As the program progresses it is expected that a number of areas of interest will be identified. It must be emphasized that any research emanating from this subtask will have passed the following filters:

1. It must address a specific issue.
2. It must have potential for significant energy impact.
3. It must not have been dealt with adequately in the previous task areas or in other research programs.

SUMMARY

This report has presented the rationale, work plan, and progress to date of a research program titled Thermal Distribution and Utilization. The subject matter of this program is the building subsystem that is used to distribute thermal energy (for heating or cooling) from the space conditioning equipment to the building spaces. Optimal utilization of the distributed energy, to minimize the amount of heating or cooling that the central equipment must produce, is an integral part of the program scope.

The reason for establishing the program is the significant annual energy savings possible--as much as 3.7 quads by the first estimate. The results of three meetings of HVAC experts were reviewed to provide a framework for initial program direction.

The work plan for the first year is based on the need for a comprehensive research plan reaching five to ten years into the future. Specific assessment activities in support of this planning effort have also been delineated.

Significant results to date include the following:

- The program rationale, scope, and direction have been defined.
- The literature on forced-air systems has been searched, and significant results have been organized and compared.
- A format and a source for data on ducts in housing have been established.
- Duct-loss factors have been identified, and a formalism for their study and quantification has been developed.
- A method has been developed for reassessing the energy savings potential to be derived from advances in thermal distribution and utilization.
- A method has been developed for rating the relative merits of alternative proposed solutions to problems of duct losses and of zoning.
- A methodology for assessing thermal interactions between zones has been developed and preliminary calculations have been performed.
- A preliminary program planning effort has been carried out for radiant heating and cooling.

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