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IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors

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Sponsor

Power System Instrumentation and Measurements Committee of the IEEE Power Engineering Society

Approved March 16, 1995

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Abstract: Diagnostic tests and measurements that are performed in the field on oil-immersed power transformers and regulators are described. Whenever possible, shunt reactors are treated in a similar manner to transformers. Tests are presented systematically in categories depending on the subsystem of the unit being examined. A diagnostic chart is included as an aid to identify the various subsystems. Additional information is provided regarding specialized test and measuring techniques.

Keywords: Oil filled transformers, regulators, reactors, diagnostic evaluation, off-line testing, field testing, windings, bushings, insulating fluids, tapchangers, core, tanks, safety.

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Introduction

(This introduction is not a part of IEEE Std 62-1995, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus.)

The condition of power apparatus is of prime importance for the successful operation of a power system. During transportation, installation, and service operation, the apparatus may be exposed to conditions that adversely affect its reliability and useful life. One of the principal aims of the maintenance engineer is to detect defects at an early stage and take appropriate corrective measures. The detection is usually achieved by means of diagnostic evaluation in the field that is performed at regular intervals as necessary. This guide describes most of the diagnostic procedures and measurements that are common practice and provides additional information in the case of more specialized techniques. Each test has an interpretation section that is provided, not to establish a standard, but merely to guide the user. There is not necessarily any direct relationship between these field tests and factory tests. For tests performed within the warranty period, the measurements should agree with the manufacturer's data when performed under similar conditions. When measurements are performed outside the warranty period on service-aged equipment, there may be some deviation between field and factory data. Interpretation of measured results is usually based on a comparison with data obtained previously on the same unit or by comparison with similar units. Many of the levels specified in this guide are not standardized; however, the values quoted have been found to be practical and are commonly used. The frequency of the tests will vary depending upon the type, size, age, and operating history of the unit. It is recommended that the user of the power apparatus establish a maintenance schedule based on these conditions and on original equipment manufacturer recommendations. The test results obtained during the periodic checks should be systematically filed in order to provide a diagnostic data base.

This guide was first published as IEE Std 62-1958, Recommended Guide for Making Dielectric Measurements in the Field. It was revised and republished as IEEE Std 62-1978, Guide for Field Testing Power Apparatus Insulation. This present revision contains more detailed descriptions of test procedures than the previous editions and also includes guidance covering visual inspection. It will therefore be published in different parts with each part covering a specific type of power apparatus.

This revision was prepared by the Diagnostic Testing Working Group under the sponsorship of the IEEE Power System Instrumentation and Measurements Committee with significant contributions from the IEEE Transformers Committee. The information in annex B is copyrighted by the Doble Engineering Company and used with permission.

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6.3 Insulating fluids (transformer-grade mineral oil)

6.3.1 General

Mineral oil is used as an insulating fluid in most types of electrical power equipment. Besides acting as an insulating fluid, in many situations it also acts as a heat transfer medium to carry off excess heat generated by the losses of the power equipment. Tests cover the determination of certain qualities, primarily degradation constituents, in service-aged oil and the diagnosis of these results with respect to the condition of the power equipment it is contained in (see IEEE Std C57.106-1991 and ASTM D 117-89).

Sampling techniques for these test methods (refer to ASTM D 923-91) should ensure that the specimen taken is representative of the insulating fluid contained within the equipment. Natural contaminants exist within the body of sampling valves; therefore the valves should be flushed before the extraction is performed in order to ensure that sample integrity is maintained.

Confirmation that a positive tank pressure exists should be made before attempting to obtain a sample. Failure to do so may result in a gas bubble entering the tank and becoming lodged between turns in the windings. This condition may result in the premature failure of the equipment.

A sufficiently large sample should be withdrawn to cover all of the tests described in 6.3. Typically 1 L should be enough. See ASTM D 923-91 and ASTM D 3613-92 for information regarding containers and sampling procedures. For tests where only some of the oil characteristics are to be checked, the quantities in table 2 are suggested.

Table 2—Minimum volumes of fluids for each test

Test	Standard	Quantity of fluid (mL)
Acidity	ASTM D 974-92	20
Color (field)	ASTM D 1524-84	10
Dielectric	ASTM D 877-87	75
Dielectric	ASTM D 1816-84a	500[a]
Dissolved gas	ASTM D 3612-93	50[a]
Interfacial tension	ASTM D 971-91	20
Interfacial tension	ASTM D 2285-85	15
Particle count	N/A	100
Power factor	ASTM D 924-92	250
Polychlorinated biphenyl	ASTM D 4059-91	10
Sludge	ASTM D 1698-84	50
Water content	ASTM D 1533-88	50
Visual	Same as color above	
Specific gravity	ASTM D 1298-85	125[a]
Color (lab)	ASTM D 1500-91	125
	Total:	1400

[a]The quantities listed above have generally been found to be needed for the test procedures. Since some equipment manufacturers make larger containers, the test laboratory should be consulted prior to sampling to ensure that the sample volume is adequate.

In most cases, the sample should be transported to the laboratory in a clean, dry container. Prolonged exposure to direct sunlight or contamination by excessive atmospheric moisture should be avoided. Many of the levels for measurements specified in 6.3 are not standardized. However, the values quoted have been found to be practical and are commonly used.

Oils in service may be placed in the following classifications based upon the evaluation of the following significant characteristics:

a) *Group I.* Oils that are in satisfactory condition for continued use
b) *Group II.* Oils that require only reconditioning for further service
c) *Group III.* Oils in poor condition (such oil should be reclaimed or disposed of depending upon economic considerations)
d) *Group IV.* Oils in such poor condition that it is technically advisable to dispose of them

All tests should be performed at least annually, but more often if the equipment is strategically located in the system.

6.3.2 Acidity, neutralization number (NN)

This test is performed to determine the acidic degradation constituents in service-aged oil.

This test should be used to indicate the relative change in an oil during use under oxidizing conditions. Acidity (neutralization) is gauged by a neutralization number (NN), which is expressed in the number of milligrams of potassium hydroxide required to neutralize the acid in a gram of oil. Transformer grade mineral oil contains only trace levels of acidic constituents when new and its NN increases as degradation of the oil occurs. A used oil having a high NN indicates that the oil is either oxidized or contaminated with materials such as varnish, paint, or other matter. This condition may be indicative of sludge formation. There should be no direct correlation between the NN and the corrosive tendency of the oil towards metals in electrical power equipment. Organic acids are detrimental to insulation systems and can induce oxidation of metals when moisture is also present. Changes occur over long periods of time. Levels are not indicative of a problem in the equipment, but of a potential threat to the internal components of the equipment. Empirical values exist with respect to condemning limits for operation of the equipment, as well as continued use of the oil (refer to ASTM D 974-92).

In a laboratory environment, a color indicator titration test should be performed, following ASTM D 974-92. The NN of the sample should be calculated according to this same procedure. Maximum recommended values of NN for different categories of oil are given in table 3.

Table 3—Suggested limits for in-service oils by group and voltage class

Type of oil	Voltage class (kV)	Acid number (mg KOH/g, max)
New oil as received from refinery		0.03
Serviced aged oil—Group I	<69	0.2
	69–288	0.2
	>345	0.1
Serviced aged oil—Group II		0.2
Serviced aged oil—Group III		0.5

6.3.3 Color

This test is performed to determine the color of service-aged oil.

This test should be used to indicate the relative change in an oil during use. Color is expressed by a numerical value (also, a color description) based on comparison with a series of color standards. There should be no direct correlation between a change in the color of the oil and a specific problem within the equipment. Changes normally occur over long periods of time. A rapidly increasing number should be indicative of a dramatic change in operating condition and generally precedes other indications of a problem. A high color number occurs in combination with the presence of oil deterioration or contamination or both. Empirical values exist with respect to condemning limits for operation of the equipment, as well as relative condition (refer to ASTM D 1500-91).

A visual test should be performed, following ASTM D 1524-84. The ASTM color for the sample should be determined using this procedure.

Interpretation: See table 4.

Table 4—Relative condition of oil based on color

Color comparator number	ASTM color	Oil condition
0.0–0.5	Clear	New oil
0.5–1.0	Pale yellow	Good oil
1.0–2.5	Yellow	Service-aged oil
2.5–4.0	Bright yellow	Marginal condition
4.0–5.5	Amber	Bad condition
5.5–7.0	Brown	Severe condition (reclaim oil)
7.0–8.5	Dark brown	Extreme condition (scrap oil)[a]

[a]Retest to confirm reading prior to scrapping oil.

6.3.4 Dielectric strength

This test is performed to determine the dielectric breakdown voltage of service-aged oil.

There are two commonly used methods to determine the dielectric breakdown voltage of oil. ASTM D 1816-84a, which utilizes spherical capped electrodes of the Verband Deutscher Elektroechniker (VDE) type in its test cell, is recommended primarily for filtered, degassed, and dehydrated oil prior to and during filling of electrical power equipment rated above 230 kV, or for testing samples of such oil from this equipment after filling. ASTM D 877-87, which utilizes flat electrodes, is recommended for all other apparatus, which is by far the majority of all electric power equipment. For this reason, 6.3.4 will concentrate primarily on this latter test. By-products of contamination and deterioration generally reduce the dielectric strength of oil. The dielectric breakdown voltage of oil is important to measure the oil's ability to withstand electrical stress without failure. High dielectric strengths do not indicate the absence of all contaminants. There should be no direct correlation between a certain breakdown voltage and failure, except in extreme cases. Empirical values exist with respect to condemning limits for operation of the equipment, as well as, relative condition (refer to ASTM D 877-87 and ASTM D 1816-84a).

This test may be satisfactorily performed in the field, but is more controllable in a laboratory environment. A visual test should be performed to ensure that the sample does not contain free water or air bubbles caused by agitation during transport. Either ASTM D 877-87 or ASTM D 1816-84a should be followed as appropriate. The breakdown voltage for the sample should be determined using this procedure. See also IEEE Std 637-1985.

Interpretation: ASTM D 877-87

Minimum dielectric breakdown voltage (kV)	Equipment class (kV)
26	≤69
26	>69–288
26	≥345

Interpretation: ASTM D 1816-84a, (0.040 in gap)

Minimum dielectric breakdown voltage (kV)	Equipment class (kV)
23	≤69
26	>69–288
26	≥345

6.3.5 Dissolved gas

This test is performed to determine the dissolved gas components in service-aged oil.

This test should be used to determine the amount of specific gases generated by an oil-filled in-service transformer. Certain combinations and quantities of these generated gases are frequently the first indication of a possible malfunction that may eventually lead to failure if not corrected. Arcing, PD, low-energy sparking, severe overloading, and overheating in the insulation system are some of the mechanisms that can result in chemical decomposition of the insulating materials and the formation of various combustible and noncombustible gases dissolved in the oil. Normal operation may also result in the formation of some gases, but not to the same extent as when a malfunction exists. Empirical values exist with respect to condemning limits for operation of the equipment, but these values are not necessarily conclusive of an impending failure. Diagnostic routines also exist to help interpret the probable cause of the gassing (refer to ASTM D 3612-93 and IEEE Std C 57.104-1991).

Precautions: The sample should preferably be obtained using a clean, moisture-free, gas-tight container to isolate it from excessive atmospheric moisture and to maintain its quantity of dissolved gases. Care should be taken to purge the container of all free gas at the time the sample is taken. See ASTM D 3613-92 for additional guidance.

This test should be performed in a laboratory environment. ASTM D 3612-93 should be followed for extraction and analysis of key dissolved gases. After determining the quantities of key dissolved gases from the sample using this procedure, a prescribed diagnostic routine to assist in interpretation of the analysis should be followed.

Interpretation: Refer to IEEE Std C57.104-1991, tables 1, 2, and 3.

It can be difficult to determine whether or not a transformer is operating normally if it has no previous dissolved gas history. Also, considerable differences of opinion exist for what is considered a "normal transformer" with acceptable concentrations of gases.

6.3.6 Interfacial tension (IFT)

This test is performed to determine the interfacial tension of service-aged oil against water.

This test method should be used to indicate the interfacial tension between an electrical insulating oil and water. This is a measurement of the molecular attractive force between their unlike molecules at the interface. This test provides a means of detecting soluble polar contaminants and products of deterioration in the oil. There is a unique relationship between IFT and NN in that the NN of the oil increases and the IFT decreases as an oil oxidizes. To a certain extent the IFT is a measure of the remaining useful life of the oil, short of its being reclaimed. Levels are not indicative of a problem in the equipment, but of a potential threat to the future operating condition of the equipment. Empirical values exist with respect to condemning limits for operation of the equipment as well as continued use of the oil (refer to ASTM D 971-91 and ASTM D 2285-85).

This test may be satisfactorily performed in the field, as well as in a laboratory environment. Generally ASTM D-971 should be followed in the laboratory and should determine the interfacial tension for the sample using the procedure. ASTM D 2285-85 should be followed in the field. See also IEEE 57.106-1991.

Interpretation: Recommended minimum levels of IFT for different conditions of oils are shown in table 5.

Table 5—Suggested limits for in-service oils by group and voltage class

Type of oil	Voltage class (kV)	Interfacial tension, dynes/cm, min
New oil as received		40
New oil received in new equipment		35
New oil after filling and standing, prior to energizing		35
Service aged oil	≤69	24
	69–288	26
	>345	30
Oil to be reconditioned or reclaimed—Group II		24
Oil to be reconditioned or reclaimed—Group III		16

6.3.7 Particle count

This test is used to determine the number, size and, to a degree, the composition of particles present in service-aged oil.

This test may be used to indicate contamination of the oil with particulate matter. The quantity of the particles in an oil can be correlated with such factors as dielectric breakdown voltage and can affect the oil's power factor. The type of particles and the quantity present will also influence these characteristics. The presence of excessive metal particles has been used as an indicator of bearing wear when the equipment utilizes cooling pumps. There are no empirical values that exist with respect to condemning limits for operation of the equipment or continued use of the oil.

Precautions: The sample should be taken when the relative humidity is <50% and should be obtained preferably using a clean, moisture-free container to isolate the sample from excessive atmospheric moisture and outside particle contamination.

After obtaining the sample in a clean 50–100 mL container, it should be transported to a laboratory for analysis. Special containers are available that have been cleaned to reduce particulate contamination. This test cannot be performed in the field. Determination of the particle count of a sample can be obtained using a light-scattering beam device. The device manufacturer's instructions should be followed for proper analysis. If diagnosis of the type of particles in the sample is desired, the use of a particle counter is preferred; however, an optical microscope may be helpful in identifying particles. Elemental analysis can be performed by complementary methods. Other tests should be made to determine if the particles are metallic and if they are magnetic. This analysis can be performed in a number of ways including the use of ferrography.

Interpretation: The number of particles in the range of 3–150 μm/10 mL of oil are counted. The following table indicates approximate particulate contamination levels for different ranges of particle counts.

Relative number of particles per 10 mL of oil	Relative condition
<1500	Normal
1500–5000	Marginal
>5000	Contaminated

NOTE—Many believe that the quantity of particles and their composition are significant only in their relation to previous levels and types. Trends observed may be significant to determine if excessive cooling pump bearing wear is being experienced. Other types of deterioration, such as may be indicated by the presence of cellulosic particles, copper, etc., may be less indicative of problems within the equipment since generally only those particles that are small enough to remain in suspension in the oil will be observed. Larger (heavier) particles are rarely ever seen since they have a tendency to fall to the bottom of the equipment's tank and are not available to be sampled or are removed in the flushing of the valve. Some agitation by ultrasonic techniques is recommended before performing the particle count.

6.3.8 Power factor

This test covers the determination of the power factor of new and service-aged oil.

This test should be used to indicate the dielectric losses in oil when used in an alternating electric field and to indicate the energy dissipated as heat. Power factor is the ratio of the power dissipated in the oil in watts to the product of the effective voltage and current in voltamperes, when tested with a sinusoidal field under prescribed conditions. A low power factor indicates low dielectric losses. It is useful as a means to ensure that sample integrity is maintained, and as an indication of changes in quality resulting from contamination and deterioration in service or as a result of handling. Oil samples that are defective often pass other standard electrical and chemical tests, yet fail this test. Empirical values exist with respect to condemning limits for operation of the equipment (refer to ASTM D 1524-84).

This test may be satisfactorily performed in the field, as well as in a laboratory environment. A visual test should be performed to ensure that the sample does not contain air bubbles due to agitation during transport. After allowing the specimen to settle in the test cell, ASTM D 924-82b should be followed in a laboratory. In the field, the recommendations of the test equipment manufacturer should be followed. The percent power factor value for the sample should be determined using these procedures and should be corrected to 20 °C for a field test. In a laboratory, tests are typically performed at 25 °C and 100 °C.

Interpretation: The maximum recommended levels of percent power factor for different categories of new and service aged oils are shown in table 6.

Table 6—Maximum suggested power factors for different categories of new and service aged oils

Type of oil	Voltage class (kV)	% Power factor at 25 °C	% Power factor at 100 °C
New oil as received		0.05	0.30
New oil received in new equipment	<69	0.15	1.50
	69–230	0.10	1.00
New oil after filling and standing, prior to energizing		0.10	—
Service aged oil—Group I	<69	0.5	
	69–288	0.5	
	≥345	0.5	
Service aged oil—Group II	<69	0.5	
	69–288	0.5	
	≥345	0.3	
Service aged oil—Group III	<69	1.0	
	69–288	0.7	
	≥345	0.3	

The power factor limits given for oil are based upon the understanding that power factor is an indicator test for contamination by excessive water (in combination with particulate matter) or polar or ionic materials in the oil. Most in-service oils have a power factor at 25 °C of <0.2%.

High levels of power factor (>0.5% at 25 °C) in oil are of concern because contaminants may collect in areas of high electrical stress and concentrate in the winding, making cleaning of the transformer difficult and masking changes in winding power factor due to other causes such as changing water content. Very high power factor (>1.0% at 25 °C) in oil may be caused by the presence of free water, which could be hazardous to the operation of a transformer. Whenever there is high power factor in oil the cause should be sought. Oxidation, free water, wet particles, contamination, and material incompatibility are all possible sources of high power factor in oil.

For further information refer to IEEE Std C57.106-1991.

6.3.9 Polychlorinated biphenyl (PCB) content

This test covers the determination of the PCB content of service-aged oil.

PCBs are regulated substances in many countries. For this reason it is important to know the present condition of all power equipment with regard to its PCB concentration. A low PCB concentration (<50 ppm) generally indicates an extremely low risk (according to the U.S. EPA) and the oil is classified as non-contaminated. A moderate PCB concentration (≥50 ppm but <500 ppm) causes the oil to be classified as contaminated. Any concentration ≥500 ppm is considered as if it were pure PCB. Because most laws deal with the PCB concentration of the involved fluid, it is most important to be aware of the PCB concentration of all insulating fluids on any given system. Local governmental regulations may require specific values of even <50 ppm.

This testing may be satisfactorily performed in the field, as well as in a laboratory environment. ASTM D 4059-91 should be followed in a laboratory. In the field, there are a number of commercially available screening kits. The expiration date should be checked before proceeding with the test. These types of tests only estimate the PCB concentration and do not give exact numerical values. It is essential that the manufacturer's recommendations be followed precisely when performing the field screening test. This type of test will give a positive indication for all chlorinated compounds whether they are PCB or not. Therefore, care should be taken not to introduce other chlorinated compounds into the procedure.

Interpretation: PCB regulations vary from area to area and state to state. Local regulators should be consulted for appropriate guidelines for particular areas.

6.3.10 Sludging condition

This test covers the determination of pentane-insoluble sludge present in service-aged oil. This test is generally not performed unless IFT is <.026 N/m (<26 dyn/cm) or the NN is >0.15 mg KOH/g oil.

Sludge is a resinous, polymeric-type substance that is partially conductive, hygroscopic, and a heat insulator. If there is water in the transformer, it will be attracted to the sludge. The presence of soluble sludge should be an indication of deterioration of the oil, presence of contaminates, or both. It serves as a warning that there may be formation of sediment. This test should be generally applicable to service-aged insulating oils and the specific test, a portion of ASTM D 1698-84, is intended to determine the extent to which the insulating oil has begun to sludge. The test has value in determining the proper procedure for performing maintenance on a transformer. If the oil has not started to sludge or is only sludging slightly, the transformer's oil may be circulated through a filtering (reclaiming) system, thus extending the life of the oil and the transformer. If the oil has progressed into sludging such that sediment exists, more dramatic maintenance procedures may be required, including the removal of the transformer from service and a thorough washing down of the insulation system, tank, and cooling system. This is necessary since sludge (sediment) and moisture will become trapped in cooling systems reducing effective cooling. There is also a possibility that the moisture-laden sludge will collect in critical regions of electrical stress and result in premature failure or, at the least, reduced heat transfer efficiencies.

A 50 mL sample of the transformer's oil should be obtained. Two mL from each sample should be drawn into 20 mL shell vials. The 10 × 1.8 cm size generally will give the best results. Ten mL of n-pentane should be added to the sample which should then be well stoppered and shaken. The sample should then be stored in a cool dark area for 24 h. After storage it should be examined for traces of sludge. The examination is performed by slowly tilting the vial so that a bubble of air runs along the vial to the bottom and causes turbulence. If sludge is present it normally will appear as a dark or cloudy mass at the bottom of the vial. Most sludges are gelatinous clumps or fine particles. If tiny solid particles are visible at the first instant of turbulence in the bottom of the vial, the test is considered positive. If none is observed, the test is negative.

Record as: A) No sludge, B) Light sludge, C) Heavy sludge

NOTE—Tiny, solid particles may not be sludge. They could be clay fines or artifacts.

Interpretation: The following table indicates the action required depending on the degree of sludge in the oil.

Level of soluble sludge/ sediment in sample	Required action
None	No action is required. Continue to monitor.
Light	Reclaim the oil.
Heavy	The oil should be scrapped. The system should thoroughly flushed and new (or reclaimed) oil should be added.

6.3.11 Visual

This test covers the determination of free water or sediment such as metal particles, insoluble sludge, carbon, fibers, dirt, etc., in service-aged oil, and the analysis and diagnosis of these findings.

If insoluble contaminants are present in the oil, valuable information concerning the condition of the transformer and its components may be obtained by filtering the oil and identifying the residue. This test method may ultimately incorporate a number of other tests such as ASTM D 1500-91 to help in the diagnosis of the potential problem.

This test is primarily designed for estimating, during a field inspection, the color and condition of a sample of oil. Follow procedure ASTM D 1524-84 to obtain results.

Interpretation: Visual examination of oil for ASTM color and the presence of sediment. The oil should be sparkling, bright, and clear.

The observation of cloudiness, particles of insulation, products of metal corrosion, or other undesirable suspended materials, as well as any unusual change in color should be followed up with more precise laboratory examination and analysis for proper diagnosis.

6.3.12 Water content

There is always some moisture present in any practical transformer. In addition, since the paper in the insulation system has a great affinity for water, most of the moisture present will be in the paper.

The dielectric strength of the paper is very sensitive to the presence of moisture as is the oil. Therefore, it is important that the moisture content be known and its concentration controlled. An estimate of the moisture content of the paper is determined by measuring the moisture content of the oil.

Water migrates between the solid and liquid insulation in a transformer with changes in load and, therefore, temperature. Consequently, the concentration of water-in-oil alone expressed in parts per million does not provide sufficient information to obtain an adequate evaluation of the insulation system dryness. Relative saturation provides a better evaluation under a wide range of operating conditions and temperatures. Even using percent saturation to evaluate insulation system dryness has some inherent biases due to the fact that water never reaches equilibrium in the solid and liquid insulation. The further from equilibrium the system is when the sample is taken, the greater the bias. The bias may be either positive or negative and can be affected by short-term transients at solid/liquid surfaces or by longer-term transitions within the thicker insulation.

Further insight concerning the relative amounts of moisture in the oil and paper insulation may be gained from figures 10 and 11. After measuring the moisture content of the oil sample in the laboratory, the percentage saturation at any temperature may be determined from figure 9. It is important that the percentage saturation does not approach 30% at the lowest temperature that the transformer may be exposed to.

Once the moisture content of the oil is determined for a given temperature, the corresponding moisture content for the paper may be estimated from figure 11. Some general guidelines for interpreting data expressed in percent saturation of water in oil and in percent moisture by dry weight of paper are presented in tables 7and 8, respectively.

Table 7—Guidelines for interpretation of % saturation of water in oil

% Water saturation of oil	Condition
0–5	Dry insulation
6–20	Moderate to wet. Lower numbers indicate fairly dry to moderate levels of water in the insulation, whereas values towards the upper limit indicate moderately wet insulation.
21–30	Wet
>30	Extremely wet

Table 8—Guidelines for interpretation of % moisture by dry weight of paper

% Moisture by dry weight in paper	Condition
0–2	Dry paper
2–4	Wet paper
>4.5	Excessively wet paper

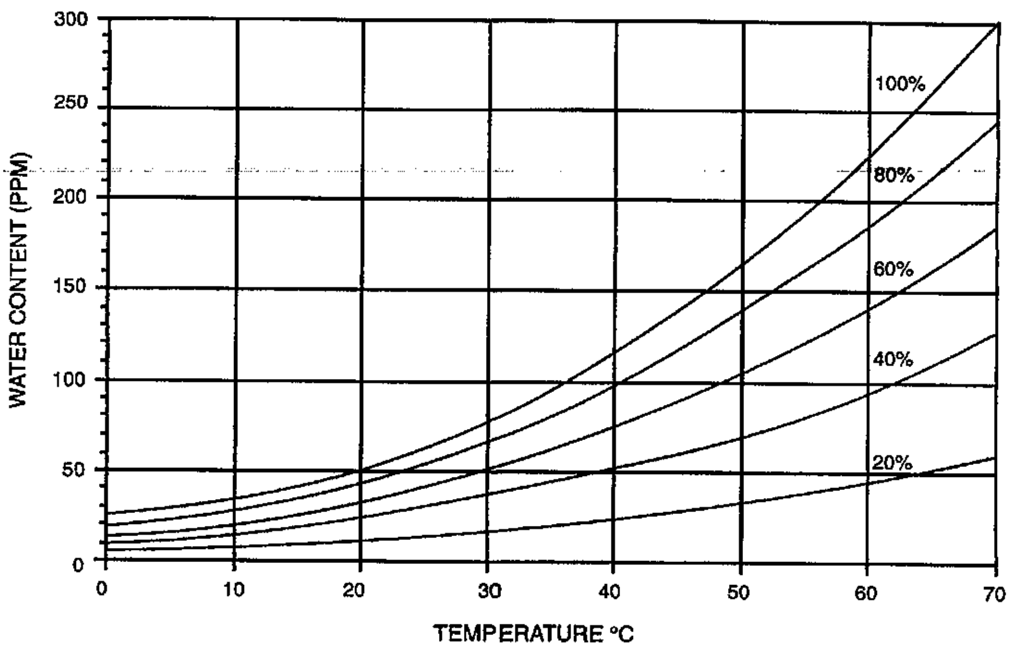
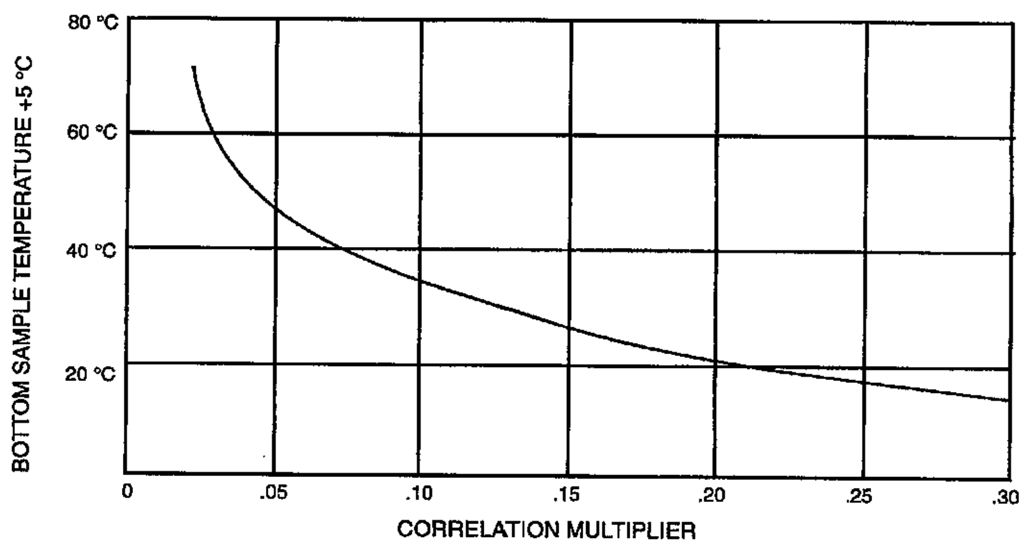


Figure 10—Moisture saturation curves for mineral oil



Correlation multiplier

To determine the % moisture by dry weight (% M/dw) of cellulosic insulation:
1) Determine PPM of H_2O.
2) Determine temperature of the bottom sample.
3) Add 5 °C to item 2.
4) Determine the correlation multiplier from graph using temperature from item 3.
5) Multiply PPM of H_2O by correlation multiplier to get % moisture by dry weight of cellulosic insulation

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Figure 11—Percent moisture by dry weight of cellulosic insulation

6.3.13 Specific gravity

This test determines the relative density of the transformer oil which is the ratio of the mass of a given volume of oil to the mass of an equal volume of water at the same temperature (15.6 °C).

The specific gravity of a mineral insulating oil influences the heat transfer rates and may be pertinent in determining suitability for use in specific applications. In cold climates ice may form in a de-energized unit so the maximum specific gravity of the dielectric oil should be at a value that will ensure that ice will not float in the unit. The oil's range should be from 0.84–0.91 (refer to ASTM D 3487-88). Water has a specific gravity of 1.0. Ice is typically 0.91. Thus in a water, oil, ice scenario both water and ice will be heavier than the oil.

This test can also be helpful in determining if the insulating fluid is oil, silicone, or askarel as the densities vary widely from fluid to fluid. ASTM D 1298-85 should be followed in the laboratory.

6.4 Tap changers

6.4.1 General

The two types of tap changers in a power transformer are tap changers for de-energized operation and LTCs. The construction of tap changers for de-energized operation is such that they shall only be operated with the transformer de-energized. Failure to do so will result in severe equipment damage, personal injury, and possible loss of life. They are normally located in the higher voltage winding of a power transformer. LTCs are designed to be operated while the transformer is energized. LTCs may be located in either the high-voltage winding or the low-voltage winding, depending on the requirements of the user, the cost effectiveness of the application, and tap changer availability.

6.4.2 General inspection procedures for LTCs

In the operating cycle of all LTCs, adjacent taps should be connected together at the point of transferring current from one tap to another. In an LTC, an impedance is introduced between these taps to control the circulating current at the point where the taps are connected together. In early designs, reactors were used as the transition impedances, while newer designs use resistors. In the load transfer operation, current is interrupted by a diverter switch. This switch may be an arcing-in-oil switch or a vacuum switch.

Equipment that is utilized as a current-interrupting device requires periodic inspection and maintenance. The frequency of inspections should be based on time in service, range of use, and number of operations. The inspection intervals described below are indicative of frequently used values. However, the actual intervals to be used are those specified by the manufacturer unless previous operational experience indicates that more frequent inspections are necessary. An initial inspection should be made on a tap changer at the end of the first year of operation. Subsequent inspections should be based on the results obtained from the initial inspection at the end of the first year of service. Regardless of the measured contact wear, the inspection interval should not exceed five years.

LTCs may be supplied in a separate compartment, which is welded or bolted to the transformer tank, or they may be located within the transformer tank. Generally, reactor transition tap changers, whether with arcing diverter switches or vacuum diverter switches, are built into a separate compartment. Resistor transition tap changers are sometimes located in a separate tank and sometimes within the main transformer tank. Those tap changers located within the transformer tank have two main components. The first is a separate cylindrical insulating tank that contains the diverter switches and transition resistors. This tank is sealed, so that the oil within it cannot mix with the main transformer oil. Directly under the sealed diverter switch tank will be the tap selector and changeover selector switch. Since no arcing occurs on these switches, they may be located in the main transformer oil. However, since they are located within the main transformer tank, inspection of these contacts cannot be made without removing the oil in the transformer tank. However, the diverter switches can be removed from this cylindrical tank for inspection without removing oil from the transformer tank.

ภาคผนวก ข.

โปรแกรม Moisture Content ภาษา C

<u>โปรแกรม Moisture Content</u>

เป็นโปรแกรมที่ใช้เขียนข้อมูลโปรแกรมลงหน่วยความจำของไมโครคอนโทรลเลอร์ AT89S8252

โปรแกรม ภาษา C

```
/**********************************************************************
***************
Project:          Water Content Tester Program (V1.0)
Filename:         SHT11.c

Prozessor:        80C51 family
Compiler:         Keil Version 7.02

Autor:            Prasitchai Fongjangvang
Company:          EGAT
**********************************************************************
**************/

#include <AT898252.h> //Microcontroller specific library, e.g. port
definitions
#include <intrins.h> //Keil library (is used for _nop()_ operation)
#include <math.h>    //Keil library
#include <stdio.h>   //Keil library

typedef union
{ unsigned int i;
  float f;
} value;

//----------------------------------------------------------------------
---------------
// modul-var
//----------------------------------------------------------------------
---------------
enum {TEMP,HUMI};
sbit START_SW = P1^6;
sbit RESET_SW = P1^7;
sbit LIGHT = P1^5;

float TOTAL_WC;
float AVERAGE_WC;


#define     DATA        P1_1
#define     SCK         P1_0

#define noACK 0
#define ACK   1
                              //adr  command  r/w
#define STATUS_REG_W 0x06     //000   0011     0
#define STATUS_REG_R 0x07     //000   0011     1
#define MEASURE_TEMP 0x03     //000   0001     1
#define MEASURE_HUMI 0x05     //000   0010     1
```

```
#define RESET        0x1e   //000  1111   0

//--- For LCD -----
sbit  RS_PIN = P2^0;              // I/O Pin for P2.0
sbit  RW_PIN = P2^1;              // I/O Pin for P2.1
sbit  EN_PIN  = P2^2;              // I/O Pin for P2.2

#define LINE1_ADDR 0x00     // Start of line 1 in the DD-Ram
#define LINE2_ADDR 0x40     // Start of line 2 in the DD-Ram

/* Display-Commands */
#define CLEAR_DISPLAY 0x01   // Clear entire display and set Display
Data Address to 0
#define LCD_HOME    0x02   // LCD Return Home
#define DD_RAM_PTR    0x80   // Address Display Data RAM pointer
#define DISP_INIT     0x38   // 8 bit 2 lines
#define INC_MODE      0x06   // Display Data RAM pointer incremented
after write
#define LCD_OFF       0x08   // LCD Display Off
#define LCD_ON            0x0C   // LCD Display On
#define LCD_CURSOR_ON 0x0F   // LCD Cursor On
#define LCD_LEFT_SHT  0x18   // LCD Left Shift Display
#define LCD_RIGHT_SHT 0x1C   // LCD Right Shift Display
#define LCD_ENTIRE        0x06       // LCD Entire Mode

//------------ Delay in 10 msec ----------------------------
void time(unsigned char ten_msec)
{
      unsigned char x;

      for (x=0;x<ten_msec;x++)
      {
            TH0=0xDC;   //0xDC @ 11.0592 MHz
            TL0=0x00;
            TF0=0;
            TR0=1;
            while (TF0==0);
            TR0=0;
      }
}

/*
 * WriteInstrReg: Write to Instruction Register of LCD Display Device
 */
void WriteInstrReg (unsigned char Instr)  {
  RS_PIN = 0;          // select instruction register
  RW_PIN = 0;          // write operation
  EN_PIN = 1;          // give operation start signal
  _nop_ (); _nop_ ();   // wait
  P0 = Instr;           // write instruction
  EN_PIN = 0;
  _nop_ (); _nop_ ();   // wait
  P0 = 0xff;            // DATA_PORT is input [prevent I/O-Port from
damage]
}

#if 0  // not required here
```

```
#endif


/*
 * WriteDataReg: Write to Data Register of LCD Display Device
 */

static void WriteDataReg (unsigned char val)  {
  RS_PIN = 1;              // select data register
  RW_PIN = 0;              // write operation
  EN_PIN = 1;              // give operation start signal
  _nop_ (); _nop_ ();       // wait
  P0 = val;                 // write value
  EN_PIN = 0;
  _nop_ (); _nop_ ();       // wait
  P0 = 0xff;                // DATA_PORT is input [prevent I/O-Port from
demage]
}

char putchar (char c)  {
  unsigned char line;
  if (c == '\n')  {
    line = 0x00; //ReadInstrReg ();
    if (line & LINE2_ADDR)  {                          // is already
in line 2
      WriteInstrReg (LINE1_ADDR | DD_RAM_PTR);   // place to start of
line 1
    }
    else  {
      WriteInstrReg (LINE2_ADDR | DD_RAM_PTR);   // place to start of
line 2
    }
  }
  else  {
      WriteDataReg (c);
  }
  return (c);
}

void init_LCD (void) {
      time(100);
      RS_PIN=0;
      WriteInstrReg(DISP_INIT);
      time(10);
      WriteInstrReg(DISP_INIT);
      time(10);
      WriteInstrReg(LCD_OFF);
      WriteInstrReg(CLEAR_DISPLAY);
      WriteInstrReg(LCD_ENTIRE);
      WriteInstrReg(LCD_HOME);
      WriteInstrReg(LCD_ON);
}

//---------- For SHT11 Interface -------------------------------------
---------------
//
//-------------------------------------------------------------------
---------------
```

```
char s_write_byte(unsigned char value)
//------------------------------------------------------------------------
---------------
// writes a byte on the Sensibus and checks the acknowledge
{
  unsigned char i,error=0;
  for (i=0x80;i>0;i/=2)             //shift bit for masking
  { if (i & value) DATA=1;          //masking value with i , write to
SENSI-BUS
    else DATA=0;
    SCK=1;                          //clk for SENSI-BUS
    _nop_();_nop_();_nop_();        //pulswith approx. 5 us
    SCK=0;
  }
  DATA=1;                           //release DATA-line
  SCK=1;                            //clk #9 for ack
  error=DATA;                       //check ack (DATA will be pulled
down by SHT11)
  SCK=0;
  return error;                     //error=1 in case of no
acknowledge
}

//------------------------------------------------------------------------
---------------
char s_read_byte(unsigned char ack)
//------------------------------------------------------------------------
---------------
// reads a byte form the Sensibus and gives an acknowledge in case of
"ack=1"
{
  unsigned char i,val=0;
  DATA=1;                           //release DATA-line
  for (i=0x80;i>0;i/=2)             //shift bit for masking
  { SCK=1;                          //clk for SENSI-BUS
    if (DATA) val=(val | i);        //read bit
    SCK=0;
  }
  DATA=!ack;                        //in case of "ack==1" pull down
DATA-Line
  SCK=1;                            //clk #9 for ack
  _nop_();_nop_();_nop_();          //pulswith approx. 5 us
  SCK=0;
  DATA=1;                           //release DATA-line
  return val;
}

//------------------------------------------------------------------------
---------------
void s_transstart(void)
//------------------------------------------------------------------------
---------------
// generates a transmission start
//        _____         ________
// DATA:       |_______|
//           ___     ___
// SCK : ___|   |___|   |______
{
```

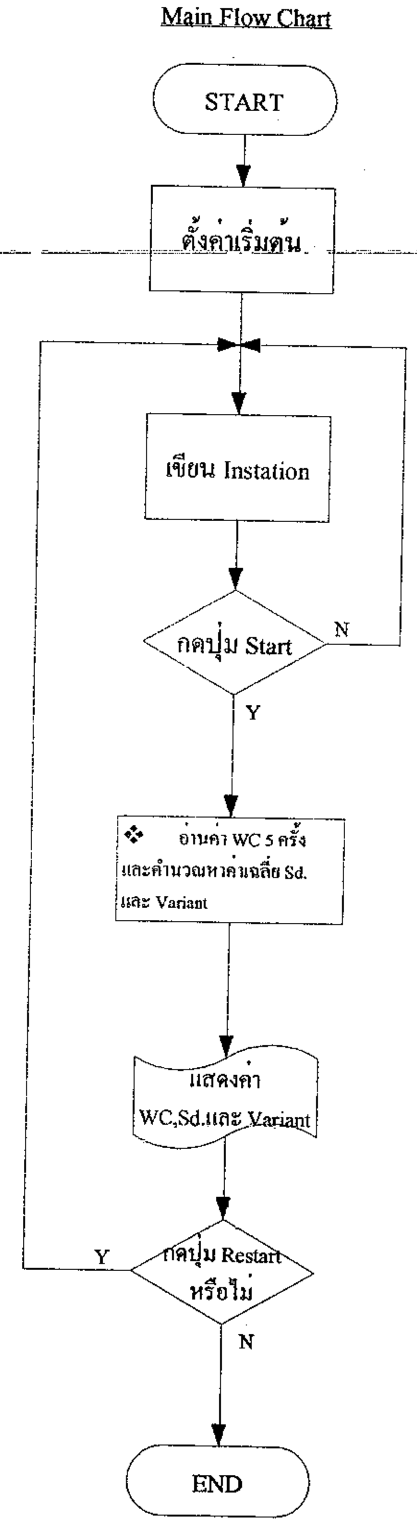
```
  DATA=1; SCK=0;                    //Initial state
  _nop_();
  SCK=1;
  _nop_();
  DATA=0;
  _nop_();
  SCK=0;
  _nop_();_nop_();_nop_();
  SCK=1;
  _nop_();
  DATA=1;
  _nop_();
  SCK=0;
}

//----------------------------------------------------------------------
---------------
void s_connectionreset(void)
//----------------------------------------------------------------------
---------------
// communication reset: DATA-line=1 and at least 9 SCK cycles
followed by transstart
//       _____________________________________________________
________
// DATA:
|_______|
//       _    _    _    _    _    _    _    _    _        ___
___
// SCK : __| |__| |__| |__| |__| |__| |__| |__| |__| |______|   |___|
|______
{
  unsigned char i;
  DATA=1; SCK=0;                    //Initial state
  for(i=0;i<9;i++)                  //9 SCK cycles
  { SCK=1;
    SCK=0;
  }
  s_transstart();                   //transmission start
}

//----------------------------------------------------------------------
---------------
char s_measure(unsigned char *p_value, unsigned char *p_checksum,
unsigned char mode)
//----------------------------------------------------------------------
---------------
// makes a measurement (humidity/temperature) with checksum
{
  unsigned error=0;
  unsigned int i;

  s_transstart();                   //transmission start
  switch(mode){                     //send command to sensor
    case TEMP     : error+=s_write_byte(MEASURE_TEMP); break;
    case HUMI     : error+=s_write_byte(MEASURE_HUMI); break;
    default     : break;
  }
```

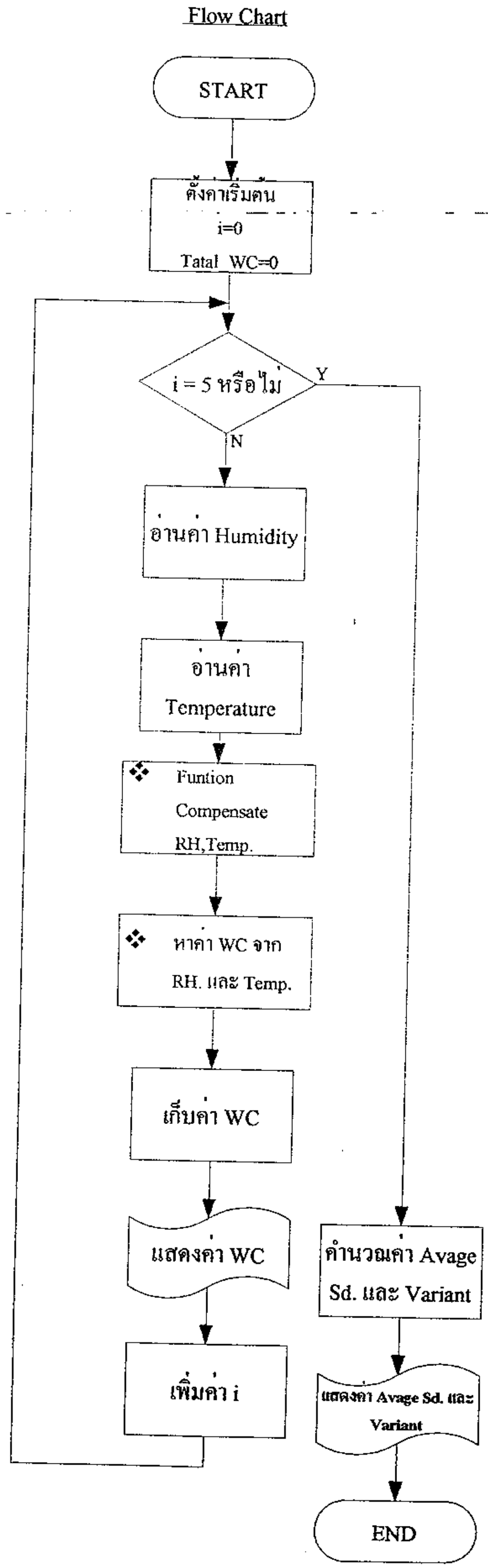
```
  for (i=0;i<65535;i++) if(DATA==0) break; //wait until sensor has
finished the measurement
  if(DATA) error+=1;                  // or timeout (~2 sec.) is
reached
  *(p_value)  =s_read_byte(ACK);      //read the first byte (MSB)
  *(p_value+1)=s_read_byte(ACK);      //read the second byte (LSB)
  *p_checksum =s_read_byte(noACK);    //read checksum
  return error;
}

//----------------------------------------------------------------------
--------------------
void calc_sth11(float *p_humidity ,float *p_temperature)
//----------------------------------------------------------------------
--------------------
// calculates temperature [°C] and humidity [%RH]
// input :  humi [Ticks] (12 bit)
//          temp [Ticks] (14 bit)
// output:  humi [%RH]
//          temp [°C]
{ const float C1=-4.0;                // for 12 Bit
  const float C2= 0.0405;             // for 12 Bit
  const float C3=-0.0000028;          // for 12 Bit
  const float T1=-0.01;               // for 14 Bit @ 5V
  const float T2=0.00008;             // for 14 Bit @ 5V

  float rh=*p_humidity;               // rh:      Humidity [Ticks] 12
Bit
  float t=*p_temperature;             // t:       Temperature [Ticks]
14 Bit
  float rh_lin;                       // rh_lin:  Humidity linear
  float rh_true;                      // rh_true: Temperature
compensated humidity
  float t_C;                          // t_C   :  Temperature [°C]

  t_C=t*0.01 - 40;                    //calc. temperature from ticks to
[°C]
  rh_lin=C3*rh*rh + C2*rh + C1;       //calc. humidity from ticks to
[%RH]
  rh_true=(t_C-25)*(T1+T2*rh)+rh_lin;   //calc. temperature
compensated humidity [%RH]
  if(rh_true>100)rh_true=100;         //cut if the value is outside of
  if(rh_true<0.1)rh_true=0.1;         //the physical possible range

  *p_temperature=t_C;                 //return temperature [°C]
  *p_humidity=rh_true;                //return humidity[%RH]
}

float calc_watercontent(float h,float t)
// calculates water content
// input : humidity [%RH], temperature [°C]
// output : water content [ppm]
{
      float watercontent;
      watercontent = (h/100*pow(10,(-1497/(273+t))+6.8423))-6.37;
//6.37 is offset with Lab.
      return watercontent;
}
```

```
//-----------------------------------------------------------------
---------------
void main()
//-----------------------------------------------------------------
---------------
{ value humi_val,temp_val;
  float water_content;//, dew_point;
  float MEASURE_WC[4];

  float SD;
  float VARIANT_WC;
  unsigned char error,checksum;
  unsigned int i,j;

//  init_uart();
  LIGHT=1;
  init_LCD();
  WriteInstrReg(LINE1_ADDR|DD_RAM_PTR);
  printf("Initialize...");
  time(100);
  s_connectionreset();
  time(100);
  WriteInstrReg(CLEAR_DISPLAY);
  time(100);
  WriteInstrReg(LINE1_ADDR|DD_RAM_PTR);
  printf("Ready...");
  time(100);
  WriteInstrReg(LINE2_ADDR|DD_RAM_PTR);
  printf("Press START ....");

  while(1)
  {
      if (START_SW == 0){
            LIGHT=0;
            TOTAL_WC=0;
            for (i=0;i<5;i++){
            WriteInstrReg(CLEAR_DISPLAY);
            error=0;
      error+=s_measure((unsigned char*) &humi_val.i,&checksum,HUMI);
//measure humidity
      error+=s_measure((unsigned char*) &temp_val.i,&checksum,TEMP);
//measure temperature
      if(error!=0) s_connectionreset();                  //in case of
an error: connection reset
      else
      {
                  humi_val.f=(float)humi_val.i;
//converts integer to float
                  temp_val.f=(float)temp_val.i;
//converts integer to float
                  calc_sth11(&humi_val.f,&temp_val.f);
//calculate humidity, temperature

      water_content=calc_watercontent(humi_val.f,temp_val.f);
          TOTAL_WC=TOTAL_WC+water_content;
                  MEASURE_WC[i]=water_content;
                  WriteInstrReg(LINE1_ADDR|DD_RAM_PTR);
```

```
                    printf("Read No.%u/5",i+1);
                    WriteInstrReg(LINE2_ADDR|DD_RAM_PTR);
                    printf("T:%3.1fC
RH:%3.1f%%",temp_val.f,humi_val.f);
                    for (j=0;j<70;j++) time(100); // 50 @ Delay for 5
seconds
                    WriteInstrReg(LINE2_ADDR|DD_RAM_PTR);
                    printf("WC:%5.2f ppm          ",water_content);
                    if (i<4){
                          for (j=0;j<400;j++) time(100);} // 600-70-
130=400 @ Delay for 1 minute
                    else {
                          for (j=0;j<70;j++) time(100); // 50 @ Delay
for 5 seconds
                    }
      } //End Read Temp. and Humidity
            } //End for i
                    LIGHT=1;
                    AVERAGE_WC=TOTAL_WC/5;
                    VARIANT_WC=0;
                    for (i=0;i<5;i++){
                          VARIANT_WC=VARIANT_WC+pow(MEASURE_WC[i]-
AVERAGE_WC,2);}
                    VARIANT_WC=VARIANT_WC/5;
                    SD=sqrt(VARIANT_WC);
                    WriteInstrReg(LINE1_ADDR|DD_RAM_PTR);
            printf("Ave.Wc:%4.2f ppm ",AVERAGE_WC);
                    WriteInstrReg(LINE2_ADDR|DD_RAM_PTR);
                    printf("Sd:%7.5f         ",SD);
                    for (j=0;j<70;j++) time(100); // 70 @ Delay for 7
seconds
                    WriteInstrReg(LINE2_ADDR|DD_RAM_PTR);
                    printf("Variant:%7.5f    ",VARIANT_WC);
                    } //End of START SW
      if (RESET_SW == 0){
      WriteInstrReg(CLEAR_DISPLAY);
            time(100);
            WriteInstrReg(LINE1_ADDR|DD_RAM_PTR);
            printf("Initialize...");
            time(100);
            s_connectionreset();
            time(100);
            WriteInstrReg(CLEAR_DISPLAY);
            time(100);
            WriteInstrReg(LINE1_ADDR|DD_RAM_PTR);
            printf("Ready...");
            time(100);
            WriteInstrReg(LINE2_ADDR|DD_RAM_PTR);
            printf("Press START ....");
      } //End of REPEAT SW
  } //End of main While loop
} //End void main()
```

Flow Chart โปรแกรมภาษาซี





ภาคผนวก ค.

Sensor SHT1X/SH7X

SENSIRION
THE SENSOR COMPANY

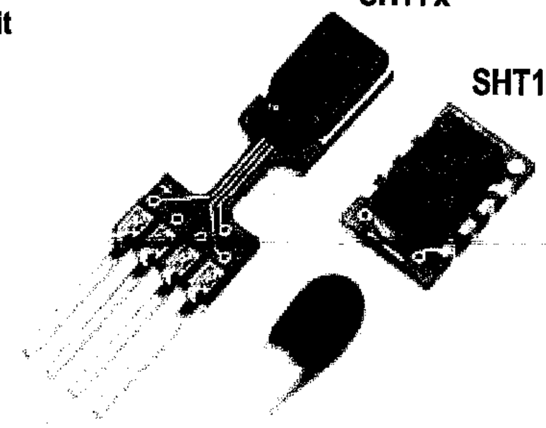
SHT1x / SHT7x

Humidity & Temperature Sensor

Evaluation Kit Available

SHT7x

SHT1x



_ Relative humidity and temperature sensors
_ Dew point
_ Fully calibrated, digital output
_ Excellent long-term stability
_ No external components required
_ Ultra low power consumption
_ Surface mountable or 4-pin fully interchangeable
_ Small size
_ Automatic power down

SHT1x / SHT7x Product Summary

The SHTxx is a single chip relative humidity and temperature multi sensor module comprising a calibrated digital output. Application of industrial CMOS processes with patented micro-machining (CMOSens® technology) ensures highest reliability and excellent long term stability. The device includes a capacitive polymer sensing element for relative humidity and a bandgap temperature sensor. Both are seamlessly coupled to a 14bit analog to digital converter and a serial interface circuit on the same chip. This results in superior signal quality, a fast response time and insensitivity to external disturbances (EMC) at a very competitive price.
Each SHTxx is individually calibrated in a precision humidity chamber with a chilled mirror hygrometer as reference. The calibration coefficients are programmed into the OTP memory. These coefficients are used internally during measurements to calibrate the signals from the sensors.
The 2-wire serial interface and internal voltage regulation allows easy and fast system integration. Its tiny size and low power consumption makes it the ultimate choice for even the most demanding applications.
The device is supplied in either a surface-mountable LCC (Leadless Chip Carrier) or as a pluggable 4-pin single-in-line type package. Customer specific packaging options may be available on request.

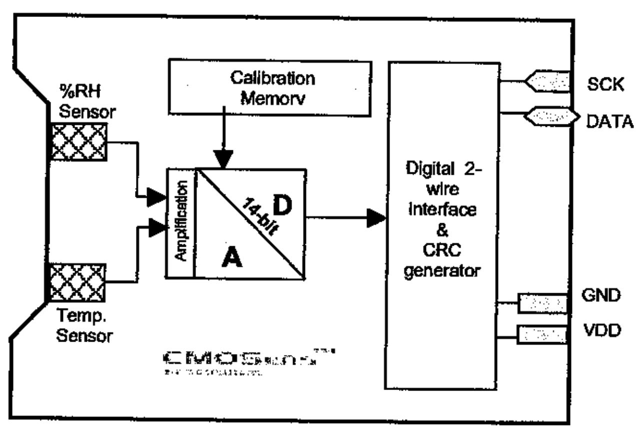
Applications

_ HVAC
_ Automotive
_ Consumer Goods
_ Weather Stations
_ (De-) Humidifiers
_ Test & Measurement
_ Data Logging
_ Automation
_ White Goods
_ Medical

Ordering Information

Part Number	Humidity accuracy [%RH]	Temperature accuracy [°C]	Package
SHT11	±3.5	±0.5 @ 25 °C	SMD (LCC)
SHT15	±2.0	±0.4 @ 5-40 °C	SMD (LCC)
SHT71	±3.5	±0.5 @ 25 °C	4-pin single-in-line
SHT75	±2.0	±0.4 @ 5-40 °C	4-pin single-in-line

Block Diagram



1 Sensor Performance Specifications

Parameter	Conditions	Min.	Typ.	Max.	Units
Humidity					
Resolution [2]		0.5	0.03	0.03	%RH
		8	12	12	bit
Repeatability			±0.1		%RH
Accuracy [1] Uncertainty	linearized	see figure 1			
Interchangeability		Fully interchangeable			
Nonlinearity	raw data		±3		%RH
	linearized		<<1		%RH
Range		0		100	%RH
Response time	1/e (63%) slowly moving air		4		s
Hysteresis			±1		%RH
Long term stability	typical		< 1		%RH/yr
Temperature					
Resolution [2]		0.04	0.01	0.01	°C
		0.07	0.02	0.02	°F
		12	14	14	bit
Repeatability			±0.1		°C
			±0.2		°F
Accuracy		see figure 1			
Range		-40		123.8	°C
		-40		254.9	°F
Response Time	1/e (63%)	5		30	s

Table 1 Sensor Performance Specifications

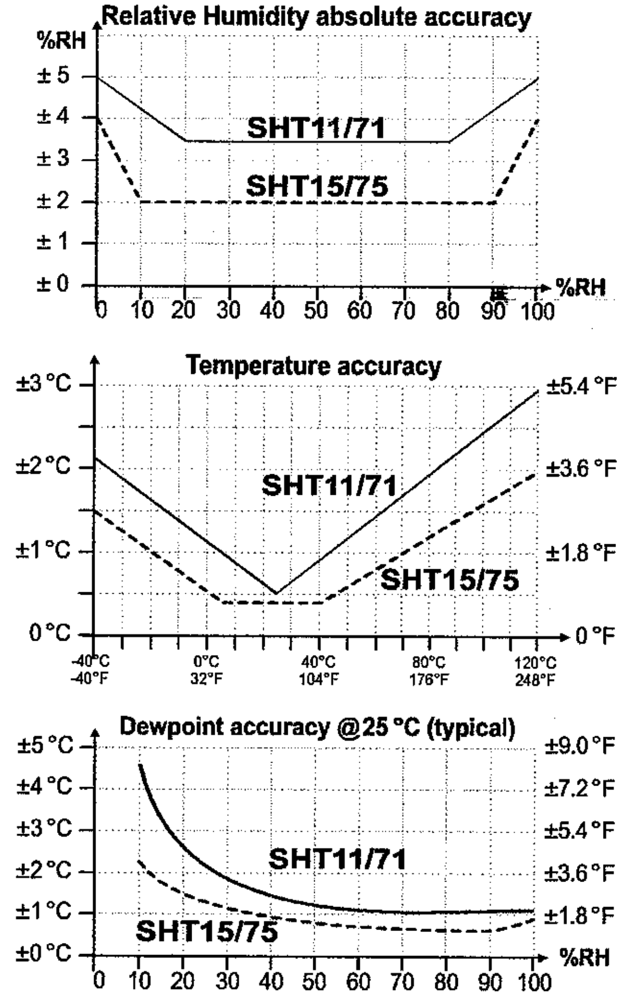


Figure 1 Rel. Humidity, Temperature and Dewpoint accuracies

2 Interface Specifications

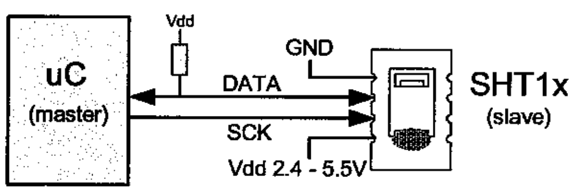


Figure 2 Typical application circuit

2.1 Power Pins

The SHTxx requires a voltage supply between 2.4 and 5.5 V. After powerup the device needs 11ms to reach its "sleep" state. No commands should be sent before that time.
Power supply pins (VDD, GND) may be decoupled with a 100 nF capacitor.

2.2 Serial Interface (Bidirectional 2-wire)

The serial interface of the SHTxx is optimized for sensor readout and power consumption and is not compatible with I²C interfaces, see FAQ for details.

2.2.1 Serial clock input (SCK)

The SCK is used to synchronize the communication between a microcontroller and the SHTxx. Since the interface consists of fully static logic there is no minimum SCK frequency.

2.2.2 Serial data (DATA)

The DATA tristate pin is used to transfer data in and out of the device. DATA **changes after the falling edge** and is **valid on the rising edge** of the serial clock SCK. During transmission the DATA line must remain stable while SCK is high. To avoid signal contention the microcontroller should only drive DATA low. An external pull-up resistor (e.g. 10 kΩ) is required to pull the signal high. (See Figure 2) Pull-up resistors are often included in I/O circuits of microcontrollers. See Table 5 for detailed IO characteristics.

(1) Each SHTxx is tested to be fully within RH accuracy specifications at 25 °C (77 °F) and 48 °C (118.4 °F)
(2) The default measurement resolution of 14bit (temperature) and 12bit (humidity) can be reduced to 12 and 8 bit through the status register.

2.2.3 *Sending a command*

To initiate a transmission, a "Transmission Start" sequence has to be issued. It consists of a lowering of the DATA line while SCK is high, followed by a low pulse on SCK and raising DATA again while SCK is still high.

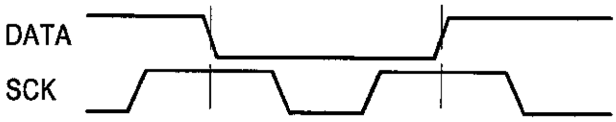


Figure 3 "Transmission Start" sequence

The subsequent command consists of three address bits (only "000" is currently supported) and five command bits. The SHTxx indicates the proper reception of a command by pulling the DATA pin low (ACK bit) after the falling edge of the 8th SCK clock. The DATA line is released (and goes high) after the falling edge of the 9th SCK clock.

Command	**Code**
Reserved	0000x
Measure Temperature	**00011**
Measure Humidity	**00101**
Read Status Register	00111
Write Status Register	00110
Reserved	0101x-1110x
Soft reset, resets the interface, clears the status register to default values wait minimum 11 ms before next command	**11110**

Table 2 SHTxx list of commands

2.2.4 *Measurement sequence (RH and T)*

After issuing a measurement command ('00000101' for RH, '00000011' for Temperature) the controller has to wait for the measurement to complete. This takes approximately 11/55/210 ms for a 8/12/14bit measurement. The exact time varies by up to ±15% with the speed of the internal oscillator. To signal the completion of a measurement, the SHTxx pulls down the data line. The controller **must** wait for this "data ready" signal before starting to toggle SCK again.

Two bytes of measurement data and one byte of CRC checksum will then be transmitted. The uC must acknowledge each byte by pulling the DATA line low. All values are MSB first, right justified. (e.g. the 5th SCK is MSB for a 12bit value, for a 8bit result the first byte is not used).

Communication terminates after the acknowledge bit of the CRC data. If CRC-8 checksum is not used the controller may terminate the communication after the measurement data LSB by keeping ack high.

The device automatically returns to sleep mode after the measurement and communication have ended.

Warning: To keep self heating below 0.1 °C the SHTxx should not be active for more than 15% of the time (e.g. max. 3 measurements / second for 12bit accuracy).

2.2.5 *Connection reset sequence*

If communication with the device is lost the following signal sequence will reset its serial interface:

While leaving DATA high, toggle SCK 9 or more times. This must be followed by a "Transmission Start" sequence preceding the next command. This sequence resets the interface only. The status register preserves its content.

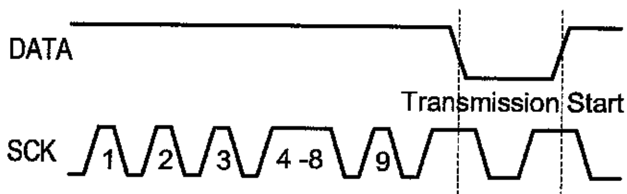


Figure 4 Connection reset sequence

2.2.6 *CRC-8 Checksum calculation*

The whole digital transmission is secured by a 8 bit checksum. It ensures that any wrong data can be detected and eliminated.

Please consult application note "CRC-8 Checksum Calculation" for information on how to calculate the CRC.

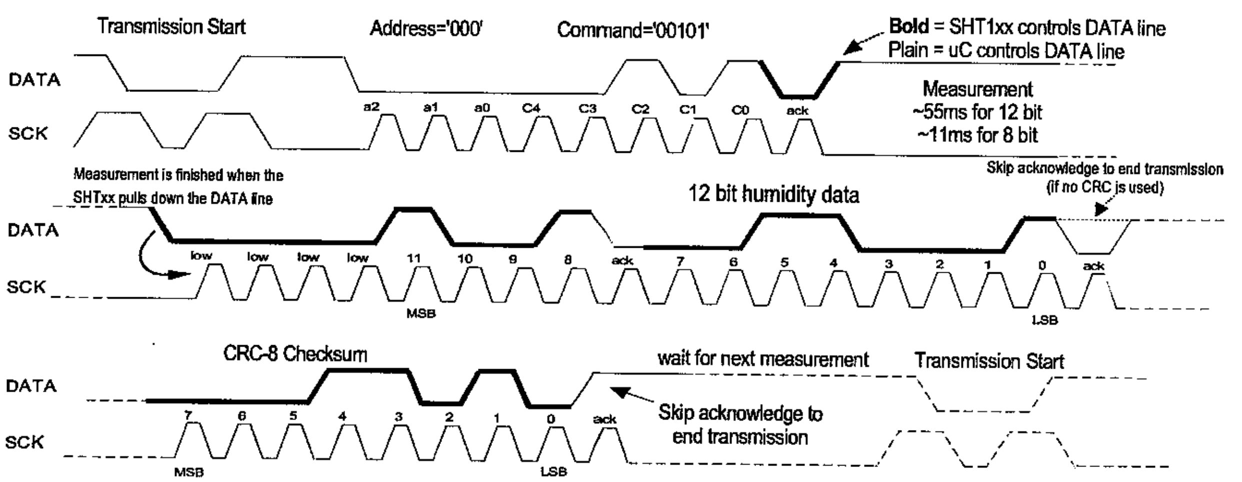


Figure 5 Example RH measurement sequence for value "0000'1001 ' 0011'0001"= 2353 = 75.79 %RH (without temperature compensation)

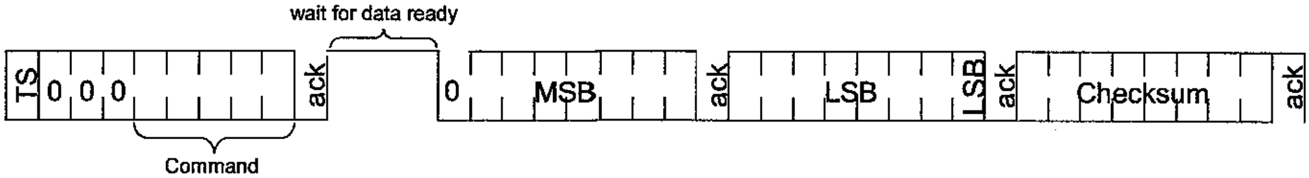


Figure 6 Overview of Measurement Sequence (TS = Transmission Start)

2.3 Status Register

Some of the advanced functions of the SHTxx are available through the status register. The following section gives a brief overview of these features. A more detailed description is available in the application note "Status Register"

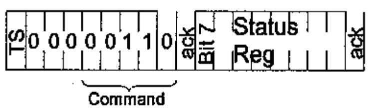


Figure 7 Status Register Write

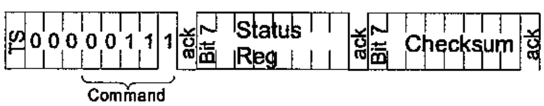


Figure 8 Status Register Read

Bit	Type	Description	Default	
7		reserved	0	
6	R	End of Battery (low voltage detection) '0' for Vdd > 2.47 '1' for Vdd < 2.47	X	No default value, bit is only updated after a measurement
5		reserved	0	
4		reserved	0	
3		For Testing only, do not use	0	
2	R/W	Heater	0	off
1	R/W	no reload from OTP	0	reload
0	R/W	'1' = 8bit RH / 12bit Temperature resolution '0' = 12bit RH / 14bit Temperature resolution	0	12bit RH 14bit Temp.

Table 3 Status Register Bits

2.3.1 Measurement resolution

The default measurement resolution of 14bit (temperature) and 12bit (humidity) can be reduced to 12 and 8bit. This is especially useful in high speed or extreme low power applications.

2.3.2 End of Battery

The "End of Battery" function detects VDD voltages below 2.47 V. Accuracy is ±0.05 V

2.3.3 Heater

An on chip heating element can be switched on. It will increase the temperature of the sensor by approximately 5°C (9 °F). Power consumption will increase by ~8 mA @ 5 V.
Applications:
By comparing temperature and humidity values before and after switching on the heater, proper functionality of both sensors can be verified.

- In high (>95 %RH) RH environments heating the sensor element will prevent condensation, improve response time and accuracy

Warning: While heated the SHTxx will show higher temperatures and a lower relative humidity than with no heating.

2.4 Electrical Characteristics[1]

VDD=5V, Temperature = 25 °C unless otherwise noted

Parameter	Conditions	Min.	Typ.	Max.	Units
Power supply DC		2.4	5	5.5	V
Supply current	measuring		550		µA
	average	2[2]	28[3]		µA
	sleep		0.3	1	µA
Low level output voltage		0		20%	Vdd
High level output voltage		75%		100%	Vdd
Low level input voltage	Negative going	0		20%	Vdd
High level input voltage	Positive going	80%		100%	Vdd
Input current on pads				1	µA
Output peak current	on			4	mA
	Tristated (off)		10		µA

Table 4 SHTxx DC Characteristics

	Parameter	Conditions	Min	Typ.	Max.	Unit
F_{SCK}	SCK frequency	VDD > 4.5 V			10	MHz
		VDD < 4.5 V			1	MHz
T_{RFO}	DATA fall time	Output load 5 pF	3.5	10	20	ns
		Output load 100 pF	30	40	200	ns
T_{CLx}	SCK hi/low time		100			ns
T_V	DATA valid time			250		ns
T_{SU}	DATA set up time		100			ns
T_{HO}	DATA hold time		0	10		ns
T_R/T_F	SCK rise/fall time			200		ns

Table 5 SHTxx I/O Signals Characteristics

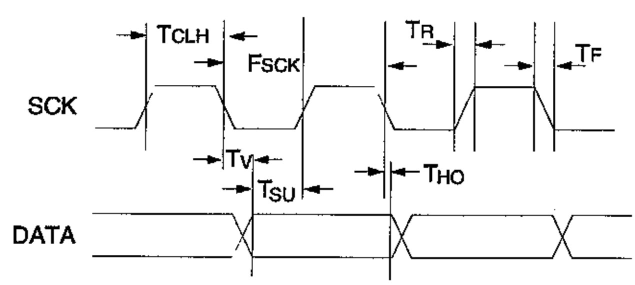


Figure 9 Timing Diagram

1) Parameters are periodically sampled and not 100% tested
(2) With one measurement of 8 bit accuracy without OTP reload per second
(3) With one measurement of 12bit accuracy per second

3 Converting Output to Physical Values

3.1 Relative Humidity

To compensate for the non-linearity of the humidity sensor and to obtain the full accuracy it is recommended to convert the readout with the following formula[1]:

$$RH_{linear} = c_1 + c_2 \bullet SO_{RH} + c_3 \bullet SO_{RH}^2$$

SO_{RH}	c_1	c_2	c_3
12 bit	-4	0.0405	$-2.8 * 10^{-6}$
8 bit	-4	0.648	$-7.2 * 10^{-4}$

Table 6 Humidity conversion coefficients

For simplified, less computation intense conversion formulas see application note "RH and Temperature Non-Linearity Compensation".

The humidity sensor has no significant voltage dependency.

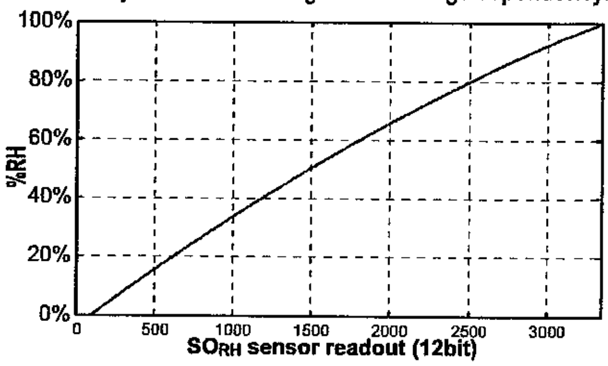


Figure 10 Conversion from SO_{RH} to relative humidity

3.1.1 Compensation of RH/Temperature dependency

For temperatures significantly different from 25 °C (~77 °F) the temperature coefficient of the RH sensor should be considered:

$$RH_{true} = (T_{°C} - 25) \bullet (t_1 + t_2 \bullet SO_{RH}) + RH_{linear}$$

SO_{RH}	t_1	t_2
12 bit	0.01	0.00008
8 bit	0.01	0.00128

Table 7 Temperature compensation coefficients

This equals ~0.12 %RH / °C @ 50 %RH

3.2 Temperature

The bandgap PTAT (Proportional To Absolute Temperature) temperature sensor is very linear by design. Use the following formula to convert from digital readout to temperature:

$$Temperature = d_1 + d_2 \bullet SO_T$$

VDD	d_1 [°C]	d_1 [°F]
5V	-40.00	-40.00
4V	-39.75	-39.50
3.5V	-39.66	-39.35
3V	-39.60	-39.28
2.5V	-39.55	-39.23

SO_T	d_2 [°C]	d_2 [°F]
14bit	0.01	0.018
12bit	0.04	0.072

Table 8 Temperature conversion coefficients

For improved accuracies in extreme temperatures with more computation intense conversion formulas see application note "RH and Temperature Non-Linearity Compensation".

3.3 Dewpoint

Since humidity and temperature are both measured on the same monolithic chip, the SHTxx allows superb dewpoint measurements. See application note "Dewpoint calculation" for more.

[1] Where SO_{RH} is the sensor output for relative humidity

4 Applications Information

4.1 Operating and Storage Conditions

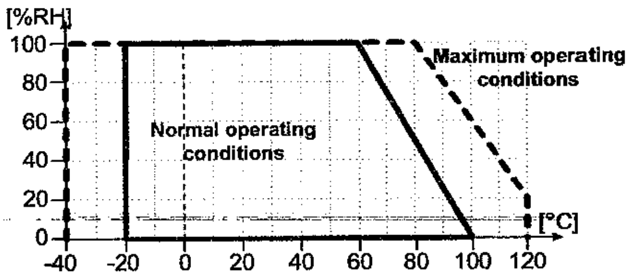


Figure 11 Recommended operating conditions

Conditions outside the recommended range may temporarily offset the RH signal up to ±3 %RH. After return to normal conditions it will slowly return towards calibration state by itself. See 4.3 "Reconditioning Procedure" to accelerate this process. Prolonged exposure to extreme conditions may accelerate ageing.

4.2 Exposure to Chemicals

Vapors may interfere with the polymer layers used for capacitive humidity sensors. The diffusion of chemicals into the polymer may cause a shift in both offset and sensitivity. In a clean environment the contaminants will slowly outgas. The reconditioning procedure described below will accelerate this process.
High levels of pollutants may cause permanent damage to the sensing polymer.

4.3 Reconditioning Procedure

The following reconditioning procedure will bring the sensor back to calibration state after exposure to extreme conditions or chemical vapors.
80-90 °C (176-194°F) at < 5 %RH for 24h (baking) followed by
20-30 °C (70-90°F) at > 74 %RH for 48h (re-hydration)

4.4 Qualifications

Extensive tests were performed in various environments. Please contact SENSIRION for additional information.

Environment	Norm	Results[1]
Temperature Cycles	JESD22-A104-B -40 °C / 125°C, 1000cy	Within Specifications
HAST Pressure Cooker	JESD22-A110-B 2.3bar 125°C 85%RH	Reversible shift by +2 %RH
Salt Atmosphere	DIN-50021ss	Within Spec.
Condensing Air	-	Within Spec.
Freezing cycles fully submerged	-20 / +90°C, 100cy 30min dwell time	Reversible shift by +2 %RH
Various Automotive Chemicals	DIN 72300-5	Within Specifications
Cigarette smoke	Equivalent to 15years in a mid-size car	Within Specifications

Table 9 Qualification tests (excerpt)

4.5 ESD (Electrostatic Discharge)

ESD immunity is qualified according to MIL STD 883E, method 3015 (Human Body Model at ±2 kV)).
Latch-up immunity is provided at a force current of ±100 mA with T_{amb} = 80 °C according to JEDEC 17.
See application note "ESD, Latchup and EMC" for more information.

4.6 Temperature Effects

The relative humidity of a gas strongly depends on its temperature. It is therefore essential to keep humidity sensors at the same temperature as the air of which the relative humidity is to be measured.
If the SHTxx shares a PCB with electronic components that give off heat it should be mounted far away and below the heat source and the housing must remain well ventilated.
To reduce heat conduction copper layers between the SHT1x and the rest of the PCB should be minimized and a slit may be milled in between. (See figure 14)

4.7 Materials Used for Sealing / Mounting

Many materials absorb humidity and will act as a buffer, increasing response times and hysteresis. Materials in the vicinity of the sensor must therefore be carefully chosen. Recommended materials are:
All Metals, LCP, POM (Delrin), PTFE (Teflon), PE, PEEK, PP, PB, PPS, PSU, PVDF, PVF
For sealing and gluing (use sparingly):
High filled epoxy for electronic packaging (e.g. glob top, underfill), and Silicone are recommended.

4.8 Membranes

A membrane can be used to prevent dirt from entering the housing and to protect the sensor. It will also reduce peak concentrations of chemical vapors. For optimal response times air volume behind the membrane must be kept to a minimum.

4.9 Light

The SHTxx is not light sensitive. Prolonged direct exposure to sunshine or strong UV radiation may age the housing.

4.10 Wiring Considerations and Signal Integrity

Carrying the SCK and DATA signal parallel and in close proximity (e.g. in wires) for more than 10cm may result in cross talk and loss of communication. This may be resolved by routing VDD and/or GND between the two data signals.
Please see the application note "ESD, Latchup and EMC" for more information.
Power supply pins (VDD, GND) should be decoupled with a 100 nF capacitor if wires are used.

(1) The temperature sensor passed all tests without any detectable drift. Package and electronics also passed 100%

5 Package Information

5.1 SHT1x (surface mountable)

Pin	Name	Comment
1	GND	Ground
2	DATA	Serial data, bidirectional
3	SCK	Serial clock, input
4	VDD	Supply 2.4 – 5.5 V
	NC	Remaining pins must be left unconnected

Table 10 SHT1x Pin Description

5.1.1 Package type

The SHT1x is supplied in a surface-mountable LCC (Leadless Chip Carrier) type package. The sensors housing consists of a Liquid Crystal Polymer (LCP) cap with epoxy glob top on a standard 0.8 mm FR4 substrate. The device is free of lead, Cd and Hg.
Device size is 7.42 x 4.88 x 2.5 mm (0.29 x 0.19 x 0.1 inch)
Weight 100 mg

The production date is printed onto the cap in white numbers in the form wwy. e.g. "351" = week 35, 2001.

5.1.2 Delivery Conditions

The SHT1x are shipped in standard IC tubes by 80 units per tube or in 12mm tape. Reels are individually labelled with barcode and human readable labels.

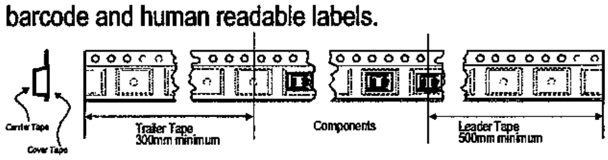


Figure 12 Tape configuration and unit orientation

5.1.3 Mounting Examples

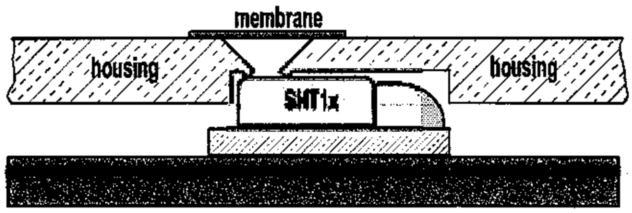


Figure 13 SHT1x housing mounting example

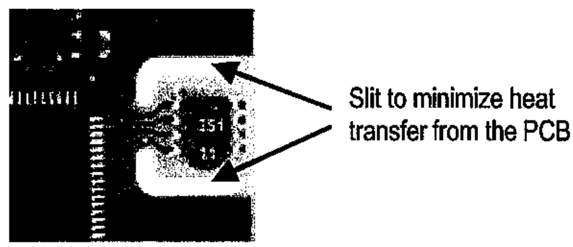


Figure 14 SHT1x PCB Mounting example

5.1.4 Soldering Information

Standard reflow soldering ovens may be used at maximum 235 °C for 20 seconds.
For manual soldering contact time must be limited to 5 seconds at up to 350 °C.
After soldering the devices should be stored at >74 %RH for at least 24h to allow the polymer to rehydrate.
Please consult the application note "Soldering procedure" for more information.

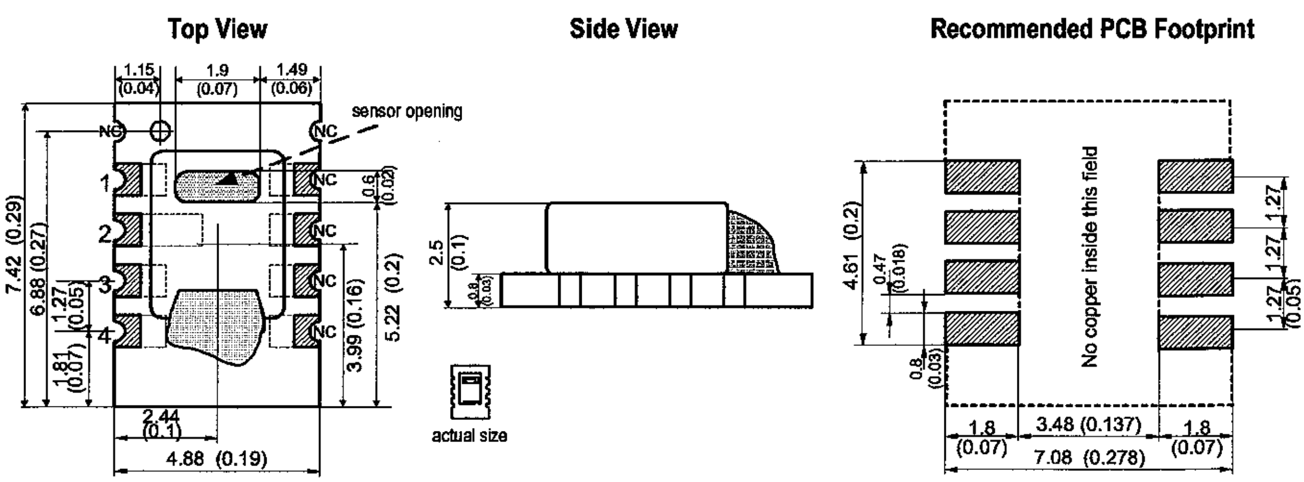


Figure 15 SHT1x drawing and footprint dimensions in mm (inch)

5.2 SHT7x (4-pin single-in-line)

Pin	Name	Comment
1	*SCK*	*Serial clock input*
2	*VDD*	*Supply 2.4 – 5.5 V*
3	*GND*	*Ground*
4	*DATA*	*Serial data bidirectional*

Table 11 SHT7x Pin Description

5.2.1 Package type[1]

The device is supplied in a single-in-line pin type package. The sensor housing consists of a Liquid Crystal Polymer (LCP) cap with epoxy glob top on a standard 0.6 mm FR4 substrate. The device is Cd and Hg free.
The sensor head is connected to the pins by a small bridge to minimize heat conduction and response times. The gold plated back side of the sensor head is connected to the GND pin.
A 100nF capacitor is mounted on the back side between VDD and GND.
All pins are gold plated to avoid corrosion. They can be soldered or mate with most 1.27 mm (0.05") sockets
e.g.: Preci-dip / Mill-Max 851-93-004-20-001 or similar
Total weight: 168 mg, weight of sensor head: 73 mg

The production date is printed onto the cap in white numbers in the form wwy. e.g. "351" = week 35, 2001.

5.2.2 Delivery Conditions

The SHT7x are shipped in 32 mm tape. These reeled parts in standard option are shipped with 500 units per 13 inch diameter reel. Reels are individually labelled with barcode and human readable labels.

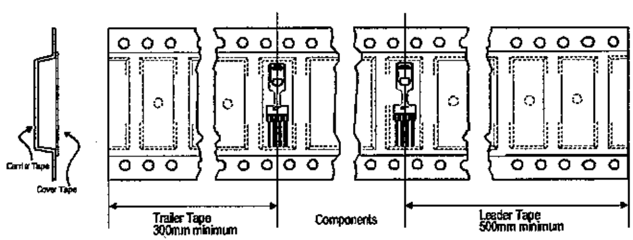


Figure 16 Tape configuration and unit orientation

5.2.3 Soldering Information

Standard wave SHT7x soldering ovens may be used at maximum 235 °C for 20 seconds.
For manual soldering contact time must be limited to 5 seconds at up to 350 °C.
After wave soldering the devices should be stored at >74 %RH for at least 24h to allow the polymer to rehydrate.
Please consult the application note "Soldering procedure" for more information.

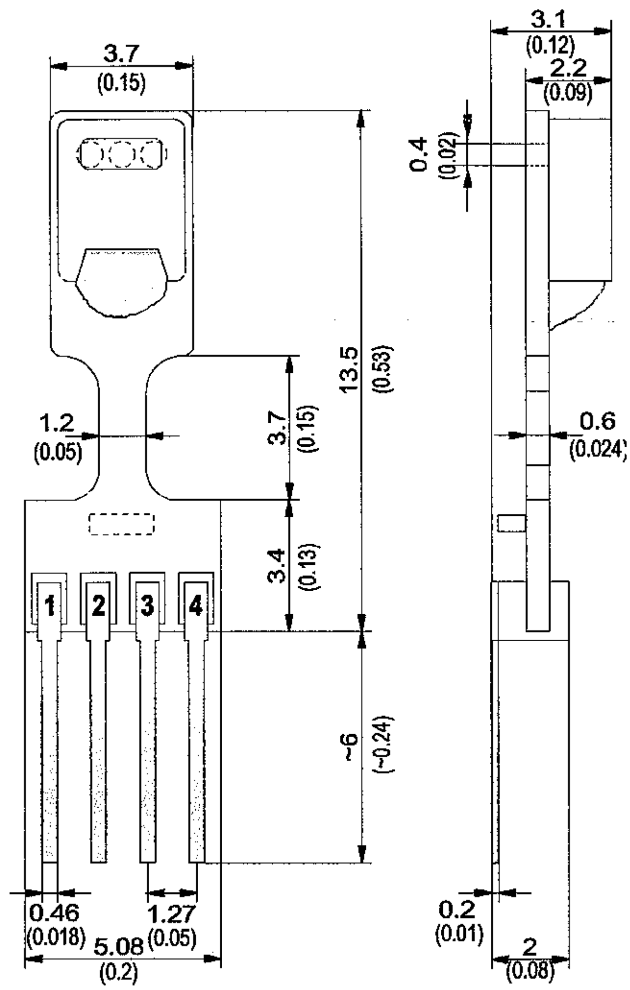


Figure 17 SHT7x dimensions in mm (inch)

[1] Other packaging options may be available on request.

6 Revision history

Date	Version	Page(s)	Changes
February 2002	Preliminary	1-9	First public release
June 2002	Preliminary		Added SHT7x information
March 2003	Final v2.0	1-9	Major remake, added application information etc. Various small modifications

The latest version of this document and all application notes can be found at:
www.sensirion.com/en/download/humiditysensor/SHT11.htm

7 Important Notices

7.1 Warning, personal injury

Do not use this product as safety or emergency stop devices or in any other application where failure of the product could result in personal injury. Failure to comply with these instructions could result in death or serious injury.

Should buyer purchase or use SENSIRION AG products for any such unintended or unauthorized application, Buyer shall indemnify and hold SENSIRION AG and its officers, employees, subsidiaries, affiliates and distributors harmless against all claims, costs, damages and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that SENSIRION AG was negligent regarding the design or manufacture of the part.

7.2 ESD Precautions

The inherent design of this component causes it to be sensitive to electrostatic discharge (ESD). To prevent ESD-induced damage and/or degradation, take normal ESD precautions when handling this product.

See application note "ESD, Latchup and EMC" for more information.

7.3 Warranty

SENSIRION AG makes no warranty, representation or guarantee regarding the suitability of its product for any particular purpose, nor does SENSIRION AG assume any liability arising out of the application or use of any product or circuit and specifically disclaims any and all liability, including without limitation consequential or incidental damages. "Typical" parameters can and do vary in different applications. All operating parameters, including "Typical" must be validated for each customer applications by customer's technical experts.

SENSIRION AG reserves the right, without further notice, to change the product specifications and/or information in this document and to improve reliability, functions and design.

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Sensirion humidity sensors are available from:

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SENSIRION
THE SENSOR COMPANY

SHTxx
Humidity & Temperature
Sensmitter

Application Note
Sample Code

1 Introduction

This application note gives an example for microcontroller C code. It includes code for:

- Readout of Humidity (RH) or Temperature (T) with basic error handling
- Calculation of RH linearization and temperature compensation
- Access to status register
- Dewpoint calculation from RH and T
- UART handling

2 Sample Code

```
/***********************************************************************************
Project:          SHT11 demo program (V2.0)
Filename:         SHT11.c

Prozessor:        80C51 family
Compiler:         Keil Version 6.14

Autor:            MST
Copyrigth:        (c) Sensirion AG
***********************************************************************************/

#include <AT89s53.h> //Microcontroller specific library, e.g. port definitions
#include <intrins.h> //Keil library (is used for _nop()_ operation)
#include <math.h>    //Keil library
#include <stdio.h>   //Keil library

typedef union
{ unsigned int i;
  float f;
} value;

//----------------------------------------------------------------------------------
// modul-var
//----------------------------------------------------------------------------------
enum {TEMP,HUMI};

#define DATA    P1_1
#define SCK     P1_0

#define noACK 0
#define ACK   1
                            //adr  command  r/w
#define STATUS_REG_W 0x06   //000   0011    0
#define STATUS_REG_R 0x07   //000   0011    1
#define MEASURE_TEMP 0x03   //000   0001    1
#define MEASURE_HUMI 0x05   //000   0010    1
#define RESET        0x1e   //000   1111    0

//----------------------------------------------------------------------------------
char s_write_byte(unsigned char value)
//----------------------------------------------------------------------------------
// writes a byte on the Sensibus and checks the acknowledge
{
  unsigned char i,error=0;
  for (i=0x80;i>0;i/=2)             //shift bit for masking
  { if (i & value) DATA=1;          //masking value with i , write to SENSI-BUS
    else DATA=0;
    SCK=1;                          //clk for SENSI-BUS
    _nop_();_nop_();_nop_();        //pulswith approx. 5 us
    SCK=0;
  }
  DATA=1;                           //release DATA-line
  SCK=1;                            //clk #9 for ack
  error=DATA;                       //check ack (DATA will be pulled down by SHT11)
  SCK=0;
```

```
  return error;                     //error=1 in case of no acknowledge
}

//----------------------------------------------------------------------------------
char s_read_byte(unsigned char ack)
//----------------------------------------------------------------------------------
// reads a byte form the Sensibus and gives an acknowledge in case of "ack=1"
{
  unsigned char i,val=0;
  DATA=1;                           //release DATA-line
  for (i=0x80;i>0;i/=2)             //shift bit for masking
  { SCK=1;                          //clk for SENSI-BUS
    if (DATA) val=(val | i);        //read bit
    SCK=0;
  }
  DATA=!ack;                        //in case of "ack==1" pull down DATA-Line
  SCK=1;                            //clk #9 for ack
  _nop_();_nop_();_nop_();          //pulswith approx. 5 us
  SCK=0;
  DATA=1;                           //release DATA-line
  return val;
}

//----------------------------------------------------------------------------------
void s_transstart(void)
//----------------------------------------------------------------------------------
// generates a transmission start
//       _____         ________
// DATA:      |_______|
//           ___     ___
// SCK : ___|   |___|   |______
{
   DATA=1; SCK=0;                   //Initial state
   _nop_();
   SCK=1;
   _nop_();
   DATA=0;
   _nop_();
   SCK=0;
   _nop_();_nop_();_nop_();
   SCK=1;
   _nop_();
   DATA=1;
   _nop_();
   SCK=0;
}

//----------------------------------------------------------------------------------
void s_connectionreset(void)
//----------------------------------------------------------------------------------
// communication reset: DATA-line=1 and at least 9 SCK cycles followed by transstart
//       _____________________________________________________         ________
// DATA:                                                      |_______|
//          _    _    _    _    _    _    _    _    _        ___     ___
// SCK : __| |__| |__| |__| |__| |__| |__| |__| |__| |______|   |___|   |______
{
  unsigned char i;
  DATA=1; SCK=0;                    //Initial state
  for(i=0;i<9;i++)                  //9 SCK cycles
  { SCK=1;
    SCK=0;
  }
  s_transstart();                   //transmission start
}

//----------------------------------------------------------------------------------
char s_softreset(void)
//----------------------------------------------------------------------------------
// resets the sensor by a softreset
{
  unsigned char error=0;
  s_connectionreset();              //reset communication
  error+=s_write_byte(RESET);       //send RESET-command to sensor
  return error;                     //error=1 in case of no response form the sensor
}

//----------------------------------------------------------------------------------
char s_read_statusreg(unsigned char *p_value, unsigned char *p_checksum)
//----------------------------------------------------------------------------------
// reads the status register with checksum (8-bit)
{
  unsigned char error=0;
```

```
float calc_dewpoint(float h,float t)
//--------------------------------------------------------------------
// calculates dew point
// input:   humidity [%RH], temperature [□C]
// output:  dew point [□C]
{ float logEx,dew_point ;
  logEx=0.66077+7.5*t/(237.3+t)+(log10(h)-2) ;
  dew_point = (logEx - 0.66077)*237.3/(0.66077+7.5-logEx) ;
  return dew_point;
}

//----------------------------------------------------------------------------------
void main()
//----------------------------------------------------------------------------------
// sample program that shows how to use SHT11 functions
// 1. connection reset
// 2. measure humidity [ticks](12 bit) and temperature [ticks](14 bit)
// 3. calculate humidity [%RH] and temperature [□C]
// 4. calculate dew point [□C]
// 5. print temperature, humidity, dew point

{ value humi_val,temp_val;
  float dew_point;
  unsigned char error,checksum;
  unsigned int i;

  init_uart();
  s_connectionreset();
  while(1)
  { error=0;
    error+=s_measure((unsigned char*) &humi_val.i,&checksum,HUMI);  //measure humidity
    error+=s_measure((unsigned char*) &temp_val.i,&checksum,TEMP);  //measure temperature
    if(error!=0) s_connectionreset();                 //in case of an error: connection reset
    else
    { humi_val.f=(float)humi_val.i;                   //converts integer to float
      temp_val.f=(float)temp_val.i;                   //converts integer to float
      calc_sth11(&humi_val.f,&temp_val.f);            //calculate humidity, temperature
      dew_point=calc_dewpoint(humi_val.f,temp_val.f); //calculate dew point
      printf("temp:%5.1fC humi:%5.1f%% dew point:%5.1fC\n",temp_val.f,humi_val.f,dew_point);
    }
    //----------wait approx. 0.8s to avoid heating up SHTxx------------------------------
    for (i=0;i<40000;i++);     //(be sure that the compiler doesn't eliminate this line!)
    //-----------------------------------------------------------------------------------
  }
}
```

3 Revision History

Date	Revision	Changes
November 20, 2001	0.9 (Preliminary)	Initial revision
February 19, 2001	1.00	
July 10, 2002	2.00	Added delay of 0.8s between measurements to prevent selfheating Connection reset only after error during transmission Checks for RH<0% and >100%
October 23, 2002	2.01	Changed sign of Temperature coefficient T1 to match datasheet.

The latest version of this document and all application notes can be found at:
www.sensirion.com/en/download/humiditysensor/SHT11.htm

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```
  s_transstart();                    //transmission start
  error=s_write_byte(STATUS_REG_R); //send command to sensor
  *p_value=s_read_byte(ACK);         //read status register (8-bit)
  *p_checksum=s_read_byte(noACK);    //read checksum (8-bit)
  return error;                      //error=1 in case of no response form the sensor
}

//----------------------------------------------------------------------------------
char s_write_statusreg(unsigned char *p_value)
//----------------------------------------------------------------------------------
// writes the status register with checksum (8-bit)
{
  unsigned char error=0;
  s_transstart();                    //transmission start
  error+=s_write_byte(STATUS_REG_W);//send command to sensor
  error+=s_write_byte(*p_value);     //send value of status register
  return error;                      //error>=1 in case of no response form the sensor
}

//----------------------------------------------------------------------------------
char s_measure(unsigned char *p_value, unsigned char *p_checksum, unsigned char mode)
//----------------------------------------------------------------------------------
// makes a measurement (humidity/temperature) with checksum
{
  unsigned error=0;
  unsigned int i;

  s_transstart();                    //transmission start
  switch(mode){                      //send command to sensor
    case TEMP  : error+=s_write_byte(MEASURE_TEMP); break;
    case HUMI  : error+=s_write_byte(MEASURE_HUMI); break;
    default      : break;
  }
  for (i=0;i<65535;i++) if(DATA==0) break; //wait until sensor has finished the measurement
  if(DATA) error+=1;                 // or timeout (~2 sec.) is reached
  *(p_value)  =s_read_byte(ACK);     //read the first byte (MSB)
  *(p_value+1)=s_read_byte(ACK);     //read the second byte (LSB)
  *p_checksum =s_read_byte(noACK);   //read checksum
  return error;
}

//----------------------------------------------------------------------------------
void init_uart()
//----------------------------------------------------------------------------------
//9600 bps @ 11.059 MHz
{SCON  = 0x52;
 TMOD  = 0x20;
 TCON  = 0x69;
 TH1   = 0xfd;
}

//----------------------------------------------------------------------------------------
void calc_sth11(float *p_humidity ,float *p_temperature)
//----------------------------------------------------------------------------------------
// calculates temperature [□C] and humidity [%RH]
// input :  humi [Ticks] (12 bit)
//          temp [Ticks] (14 bit)
// output:  humi [%RH]
//          temp [□C]
{ const float C1=-4.0;              // for 12 Bit
  const float C2= 0.0405;           // for 12 Bit
  const float C3=-0.0000028;        // for 12 Bit
  const float T1=0.01;              // for 14 Bit @ 5V
  const float T2=0.00008;           // for 14 Bit @ 5V

  float rh=*p_humidity;             // rh:      Humidity [Ticks] 12 Bit
  float t=*p_temperature;           // t:       Temperature [Ticks] 14 Bit
  float rh_lin;                     // rh_lin:  Humidity linear
  float rh_true;                    // rh_true: Temperature compensated humidity
  float t_C;                        // t_C   :  Temperature [□C]

  t_C=t*0.01 - 40;                  //calc. Temperature from ticks to [□C]
  rh_lin=C3*rh*rh + C2*rh + C1;     //calc. Humidity from ticks to [%RH]
  rh_true=(t_C-25)*(T1+T2*rh)+rh_lin;   //calc. Temperature compensated humidity [%RH]
  if(rh_true>100)rh_true=100;       //cut if the value is outside of
  if(rh_true<0.1)rh_true=0.1;       //the physical possible range

  *p_temperature=t_C;               //return temperature [□C]
  *p_humidity=rh_true;              //return humidity[%RH]
}

//----------------------------------------------------------------------
```

ภาคผนวก ง.

Microcontroller AT89S8252

Features

- Compatible with MCS®51 Products
- 8K Bytes of In-System Reprogrammable Downloadable Flash Memory
  - SPI Serial Interface for Program Downloading
  - Endurance: 1,000 Write/Erase Cycles
- 2K Bytes EEPROM
  - Endurance: 100,000 Write/Erase Cycles
- 4V to 6V Operating Range
- Fully Static Operation: 0 Hz to 24 MHz
- Three-level Program Memory Lock
- 256 x 8-bit Internal RAM
- 32 Programmable I/O Lines
- Three 16-bit Timer/Counters
- Nine Interrupt Sources
- Programmable UART Serial Channel
- SPI Serial Interface
- Low-power Idle and Power-down Modes
- Interrupt Recovery from Power-down
- Programmable Watchdog Timer
- Dual Data Pointer
- Power-off Flag

8-bit Microcontroller with 8K Bytes Flash

AT89S8252

Description

The AT89S8252 is a low-power, high-performance CMOS 8-bit microcontroller with 8K bytes of downloadable Flash programmable and erasable read-only memory and 2K bytes of EEPROM. The device is manufactured using Atmel's high-density nonvolatile memory technology and is compatible with the industry-standard 80C51 instruction set and pinout. The on-chip downloadable Flash allows the program memory to be reprogrammed In-System through an SPI serial interface or by a conventional nonvolatile memory programmer. By combining a versatile 8-bit CPU with downloadable Flash on a monolithic chip, the Atmel AT89S8252 is a powerful microcontroller, which provides a highly-flexible and cost-effective solution to many embedded control applications.

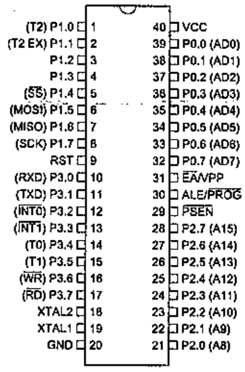
The AT89S8252 provides the following standard features: 8K bytes of downloadable Flash, 2K bytes of EEPROM, 256 bytes of RAM, 32 I/O lines, programmable watchdog timer, two data pointers, three 16-bit timer/counters, a six-vector two-level interrupt architecture, a full duplex serial port, on-chip oscillator, and clock circuitry. In addition, the AT89S8252 is designed with static logic for operation down to zero frequency and supports two software selectable power saving modes. The Idle Mode stops the CPU while allowing the RAM, timer/counters, serial port, and interrupt system to continue functioning. The Power-down mode saves the RAM contents but freezes the oscillator, disabling all other chip functions until the next external interrupt or hardware reset.

The downloadable Flash can be changed a single byte at a time and is accessible through the SPI serial interface. Holding RESET active forces the SPI bus into a serial programming interface and allows the program memory to be written to or read from unless lock bits have been activated.

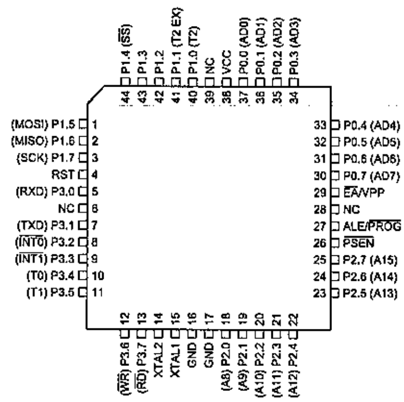
0401F–MICRO–11/03

Pin Configurations

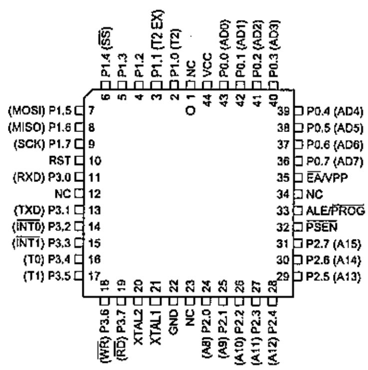
PDIP



TQFP



PLCC



Pin Description

VCC

Supply voltage.

GND

Ground.

Port 0

Port 0 is an 8-bit open drain bi-didirectional I/O port. As an output port, each pin can sink eight TTL inputs. When 1s are written to port 0 pins, the pins can be used as high-impedance inputs.

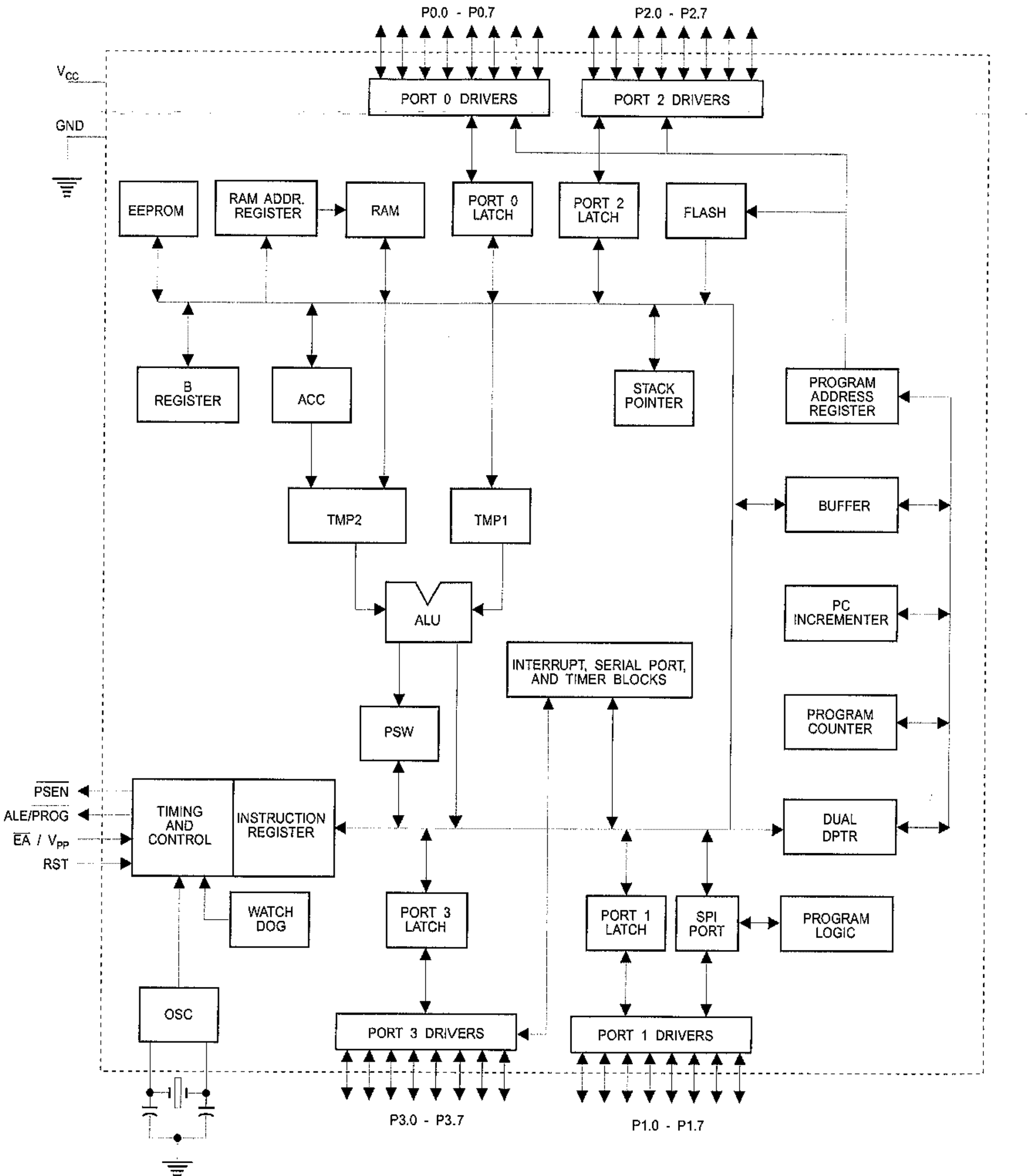
Port 0 can also be configured to be the multiplexed low-order address/data bus during accesses to external program and data memory. In this mode, P0 has internal pull-ups.

Port 0 also receives the code bytes during Flash programming and outputs the code bytes during program verification. External pull-ups are required during program verification.

Port 1

Port 1 is an 8-bit bi-directional I/O port with internal pull-ups. The Port 1 output buffers can sink/source four TTL inputs. When 1s are written to Port 1 pins, they are pulled high by the internal pull-ups and can be used as inputs. As inputs, Port 1 pins that are externally being pulled low will source current (I_{IL}) because of the internal pull-ups.

Block Diagram



Some Port 1 pins provide additional functions. P1.0 and P1.1 can be configured to be the timer/counter 2 external count input (P1.0/T2) and the timer/counter 2 trigger input (P1.1/T2EX), respectively.

Furthermore, P1.4, P1.5, P1.6, and P1.7 can be configured as the SPI slave port select, data input/output and shift clock input/output pins as shown in the following table.

Port Pin	Alternate Functions
P1.0	T2 (external count input to Timer/Counter 2), clock-out
P1.1	T2EX (Timer/Counter 2 capture/reload trigger and direction control)
P1.4	$\overline{\text{SS}}$ (Slave port select input)
P1.5	MOSI (Master data output, slave data input pin for SPI channel)
P1.6	MISO (Master data input, slave data output pin for SPI channel)
P1.7	SCK (Master clock output, slave clock input pin for SPI channel)

Port 1 also receives the low-order address bytes during Flash programming and verification.

Port 2

Port 2 is an 8-bit bi-directional I/O port with internal pull-ups. The Port 2 output buffers can sink/source four TTL inputs. When 1s are written to Port 2 pins, they are pulled high by the internal pull-ups and can be used as inputs. As inputs, Port 2 pins that are externally being pulled low will source current (I_{IL}) because of the internal pull-ups.

Port 2 emits the high-order address byte during fetches from external program memory and during accesses to external data memory that use 16-bit addresses (MOVX @ DPTR). In this application, Port 2 uses strong internal pull-ups when emitting 1s. During accesses to external data memory that use 8-bit addresses (MOVX @ RI), Port 2 emits the contents of the P2 Special Function Register.

Port 2 also receives the high-order address bits and some control signals during Flash programming and verification.

Port 3

Port 3 is an 8-bit bi-directional I/O port with internal pull-ups. The Port 3 output buffers can sink/source four TTL inputs. When 1s are written to Port 3 pins, they are pulled high by the internal pull-ups and can be used as inputs. As inputs, Port 3 pins that are externally being pulled low will source current (I_{IL}) because of the pull-ups.

Port 3 receives some control signals for Flash programming and verification.

Port 3 also serves the functions of various special features of the AT89S8252, as shown in the following table.

Port Pin	Alternate Functions
P3.0	RXD (serial input port)
P3.1	TXD (serial output port)
P3.2	$\overline{INT0}$ (external interrupt 0)
P3.3	$\overline{INT1}$ (external interrupt 1)
P3.4	T0 (timer 0 external input)
P3.5	T1 (timer 1 external input)
P3.6	$\overline{WR}$ (external data memory write strobe)
P3.7	$\overline{RD}$ (external data memory read strobe)

RST

Reset input. A high on this pin for two machine cycles while the oscillator is running resets the device.

ALE/$\overline{PROG}$

Address Latch Enable is an output pulse for latching the low byte of the address during accesses to external memory. This pin is also the program pulse input ($\overline{PROG}$) during Flash programming.

In normal operation, ALE is emitted at a constant rate of 1/6 the oscillator frequency and may be used for external timing or clocking purposes. Note, however, that one ALE pulse is skipped during each access to external data memory.

If desired, ALE operation can be disabled by setting bit 0 of SFR location 8EH. With the bit set, ALE is active only during a MOVX or MOVC instruction. Otherwise, the pin is weakly pulled high. Setting the ALE-disable bit has no effect if the microcontroller is in external execution mode.

$\overline{PSEN}$

Program Store Enable is the read strobe to external program memory.

When the AT89S8252 is executing code from external program memory, $\overline{PSEN}$ is activated twice each machine cycle, except that two $\overline{PSEN}$ activations are skipped during each access to external data memory.

$\overline{EA}$/VPP

External Access Enable. $\overline{EA}$ must be strapped to GND in order to enable the device to fetch code from external program memory locations starting at 0000H up to FFFFH. Note, however, that if lock bit 1 is programmed, $\overline{EA}$ will be internally latched on reset.

$\overline{EA}$ should be strapped to V_{CC} for internal program executions. This pin also receives the 12-volt programming enable voltage (V_{PP}) during Flash programming when 12-volt programming is selected.

XTAL1

Input to the inverting oscillator amplifier and input to the internal clock operating circuit.

XTAL2

Output from the inverting oscillator amplifier.

Special Function Registers

A map of the on-chip memory area called the Special Function Register (SFR) space is shown in Table 1.

Note that not all of the addresses are occupied, and unoccupied addresses may not be implemented on the chip. Read accesses to these addresses will in general return random data, and write accesses will have an indeterminate effect.

User software should not write 1s to these unlisted locations, since they may be used in future products to invoke new features. In that case, the reset or inactive values of the new bits will always be 0.

Timer 2 Registers Control and status bits are contained in registers T2CON (shown in Table 2) and T2MOD (shown in Table 9) for Timer 2. The register pair (RCAP2H, RCAP2L) are the Capture/Reload registers for Timer 2 in 16-bit capture mode or 16-bit auto-reload mode.

Table 1. AT89S8252 SFR Map and Reset Values

0F8H									0FFH
0F0H	B 00000000								0F7H
0E8H									0EFH
0E0H	ACC 00000000								0E7H
0D8H									0DFH
0D0H	PSW 00000000					SPCR 000001XX			0D7H
0C8H	T2CON 00000000	T2MOD XXXXXX00	RCAP2L 00000000	RCAP2H 00000000	TL2 00000000	TH2 00000000			0CFH
0C0H									0C7H
0B8H	IP XX000000								0BFH
0B0H	P3 11111111								0B7H
0A8H	IE 0X000000		SPSR 00XXXXXX						0AFH
0A0H	P2 11111111								0A7H
98H	SCON 00000000	SBUF XXXXXXXX							9FH
90H	P1 11111111						WMCON 00000010		97H
88H	TCON 00000000	TMOD 00000000	TL0 00000000	TL1 00000000	TH0 00000000	TH1 00000000			8FH
80H	P0 11111111	SP 00000111	DP0L 00000000	DP0H 00000000	DP1L 00000000	DP1H 00000000	SPDR XXXXXXXX	PCON 0XXX0000	87H

Table 2. T2CON – Timer/Counter 2 Control Register

T2CON Address = 0C8H | Reset Value = 0000 0000B

Bit Addressable

	TF2	EXF2	RCLK	TCLK	EXEN2	TR2	$C/\overline{T2}$	$CP/\overline{RL2}$
Bit	7	6	5	4	3	2	1	0

Symbol	Function
TF2	Timer 2 overflow flag set by a Timer 2 overflow and must be cleared by software. TF2 will not be set when either RCLK = 1 or TCLK = 1.
EXF2	Timer 2 external flag set when either a capture or reload is caused by a negative transition on T2EX and EXEN2 = 1. When Timer 2 interrupt is enabled, EXF2 = 1 will cause the CPU to vector to the Timer 2 interrupt routine. EXF2 must be cleared by software. EXF2 does not cause an interrupt in up/down counter mode (DCEN = 1).
RCLK	Receive clock enable. When set, causes the serial port to use Timer 2 overflow pulses for its receive clock in serial port Modes 1 and 3. RCLK = 0 causes Timer 1 overflows to be used for the receive clock.
TCLK	Transmit clock enable. When set, causes the serial port to use Timer 2 overflow pulses for its transmit clock in serial port Modes 1 and 3. TCLK = 0 causes Timer 1 overflows to be used for the transmit clock.
EXEN2	Timer 2 external enable. When set, allows a capture or reload to occur as a result of a negative transition on T2EX if Timer 2 is not being used to clock the serial port. EXEN2 = 0 causes Timer 2 to ignore events at T2EX.
TR2	Start/Stop control for Timer 2. TR2 = 1 starts the timer.
$C/\overline{T2}$	Timer or counter select for Timer 2. $C/\overline{T2}$ = 0 for timer function. $C/\overline{T2}$ = 1 for external event counter (falling edge triggered).
$CP/\overline{RL2}$	Capture/Reload select. $CP/\overline{RL2}$ = 1 causes captures to occur on negative transitions at T2EX if EXEN2 = 1. $CP/\overline{RL2}$ = 0 causes automatic reloads to occur when Timer 2 overflows or negative transitions occur at T2EX when EXEN2 = 1. When either RCLK or TCLK = 1, this bit is ignored and the timer is forced to auto-reload on Timer 2 overflow.

Watchdog and Memory Control Register The WMCON register contains control bits for the Watchdog Timer (shown in Table 3). The EEMEN and EEMWE bits are used to select the 2K bytes on-chip EEPROM, and to enable byte-write. The DPS bit selects one of two DPTR registers available.

Table 3. WMCON—Watchdog and Memory Control Register

WMCON Address = 96H

Reset Value = 0000 0010B

	PS2	PS1	PS0	EEMWE	EEMEN	DPS	WDTRST	WDTEN
Bit	7	6	5	4	3	2	1	0

Symbol	Function
PS2 PS1 PS0	Prescaler Bits for the Watchdog Timer. When all three bits are set to "0", the watchdog timer has a nominal period of 16 ms. When all three bits are set to "1", the nominal period is 2048 ms.
EEMWE	EEPROM Data Memory Write Enable Bit. Set this bit to "1" before initiating byte write to on-chip EEPROM with the MOVX instruction. User software should set this bit to "0" after EEPROM write is completed.
EEMEN	Internal EEPROM Access Enable. When EEMEN = 1, the MOVX instruction with DPTR will access on-chip EEPROM instead of external data memory. When EEMEN = 0, MOVX with DPTR accesses external data memory.
DPS	Data Pointer Register Select. DPS = 0 selects the first bank of Data Pointer Register, DP0, and DPS = 1 selects the second bank, DP1
WDTRST RDY/$\overline{BSY}$	Watchdog Timer Reset and EEPROM Ready/$\overline{Busy}$ Flag. Each time this bit is set to "1" by user software, a pulse is generated to reset the watchdog timer. The WDTRST bit is then automatically reset to "0" in the next instruction cycle. The WDTRST bit is Write-Only. This bit also serves as the RDY/$\overline{BSY}$ flag in a Read-Only mode during EEPROM write. RDY/$\overline{BSY}$ = 1 means that the EEPROM is ready to be programmed. While programming operations are being executed, the RDY/$\overline{BSY}$ bit equals "0" and is automatically reset to "1" when programming is completed.
WDTEN	Watchdog Timer Enable Bit. WDTEN = 1 enables the watchdog timer and WDTEN = 0 disables the watchdog timer.

SPI Registers Control and status bits for the Serial Peripheral Interface are contained in registers SPCR (shown in Table 4) and SPSR (shown in Table 5). The SPI data bits are contained in the SPDR register. Writing the SPI data register during serial data transfer sets the Write Collision bit, WCOL, in the SPSR register. The SPDR is double buffered for writing and the values in SPDR are not changed by Reset.

Interrupt Registers The global interrupt enable bit and the individual interrupt enable bits are in the IE register. In addition, the individual interrupt enable bit for the SPI is in the SPCR register. Two priorities can be set for each of the six interrupt sources in the IP register.

Dual Data Pointer Registers To facilitate accessing both internal EEPROM and external data memory, two banks of 16-bit Data Pointer Registers are provided: DP0 at SFR address locations 82H-83H and DP1 at 84H-85H. Bit DPS = 0 in SFR WMCON selects DP0 and DPS = 1 selects DP1. The user should **ALWAYS** initialize the DPS bit to the appropriate value before accessing the respective Data Pointer Register.

Power Off Flag The Power Off Flag (POF) is located at bit_4 (PCON.4) in the PCON SFR. POF is set to "1" during power up. It can be set and reset under software control and is not affected by RESET.

Table 4. SPCR – SPI Control Register

SPCR Address = D5H — Reset Value = 0000 01XXB

	SPIE	SPE	DORD	MSTR	CPOL	CPHA	SPR1	SPR0
Bit	7	6	5	4	3	2	1	0

Symbol	Function
SPIE	SPI Interrupt Enable. This bit, in conjunction with the ES bit in the IE register, enables SPI interrupts: SPIE = 1 and ES = 1 enable SPI interrupts. SPIE = 0 disables SPI interrupts.
SPE	SPI Enable. SPI = 1 enables the SPI channel and connects $\overline{SS}$, MOSI, MISO and SCK to pins P1.4, P1.5, P1.6, and P1.7. SPI = 0 disables the SPI channel.
DORD	Data Order. DORD = 1 selects LSB first data transmission. DORD = 0 selects MSB first data transmission.
MSTR	Master/Slave Select. MSTR = 1 selects Master SPI mode. MSTR = 0 selects Slave SPI mode.
CPOL	Clock Polarity. When CPOL = 1, SCK is high when idle. When CPOL = 0, SCK of the master device is low when not transmitting. Please refer to figure on SPI Clock Phase and Polarity Control.
CPHA	Clock Phase. The CPHA bit together with the CPOL bit controls the clock and data relationship between master and slave. Please refer to figure on SPI Clock Phase and Polarity Control.
SPR0 SPR1	SPI Clock Rate Select. These two bits control the SCK rate of the device configured as master. SPR1 and SPR0 have no effect on the slave. The relationship between SCK and the oscillator frequency, $F_{OSC.}$, is as follows: SPR1 SPR0 SCK = $F_{OSC.}$ divided by 0 0 4 0 1 16 1 0 64 1 1 128

Table 5. SPSR – SPI Status Register

SPSR Address = AAH								Reset Value = 00XX XXXXB
	SPIF	WCOL	–	–	–	–	–	–
Bit	7	6	5	4	3	2	1	0

Symbol	Function
SPIF	SPI Interrupt Flag. When a serial transfer is complete, the SPIF bit is set and an interrupt is generated if SPIE = 1 and ES = 1. The SPIF bit is cleared by reading the SPI status register with SPIF and WCOL bits set, and then reading/writing the SPI data register.
WCOL	Write Collision Flag. The WCOL bit is set if the SPI data register is written during a data transfer. During data transfer, the result of reading the SPDR register may be incorrect, and writing to it has no effect. The WCOL bit (and the SPIF bit) are cleared by reading the SPI status register with SPIF and WCOL set, and then accessing the SPI data register.

Table 6. SPDR – SPI Data Register

SPDR Address = 86H								Reset Value = unchanged
	SPD7	SPD6	SPD5	SPD4	SPD3	SPD2	SPD1	SPD0
Bit	7	6	5	4	3	2	1	0

Data Memory – EEPROM and RAM

The AT89S8252 implements 2K bytes of on-chip EEPROM for data storage and 256 bytes of RAM. The upper 128 bytes of RAM occupy a parallel space to the Special Function Registers. That means the upper 128 bytes have the same addresses as the SFR space but are physically separate from SFR space.

When an instruction accesses an internal location above address 7FH, the address mode used in the instruction specifies whether the CPU accesses the upper 128 bytes of RAM or the SFR space. Instructions that use direct addressing access SFR space.

For example, the following direct addressing instruction accesses the SFR at location 0A0H (which is P2).

```
MOV 0A0H, #data
```

Instructions that use indirect addressing access the upper 128 bytes of RAM. For example, the following indirect addressing instruction, where R0 contains 0A0H, accesses the data byte at address 0A0H, rather than P2 (whose address is 0A0H).

```
MOV @R0, #data
```

Note that stack operations are examples of indirect addressing, so the upper 128 bytes of data RAM are available as stack space.

The on-chip EEPROM data memory is selected by setting the EEMEN bit in the WMCON register at SFR address location 96H. The EEPROM address range is from 000H to 7FFH. The MOVX instructions are used to access the EEPROM. To access off-chip data memory with the MOVX instructions, the EEMEN bit needs to be set to "0".

The EEMWE bit in the WMCON register needs to be set to "1" before any byte location in the EEPROM can be written. User software should reset EEMWE bit to "0" if no further EEPROM write is required. EEPROM write cycles in the serial programming mode are self-timed and typically take 2.5 ms. The progress of EEPROM write can be monitored by reading the RDY/$\overline{\text{BSY}}$ bit (read-only) in SFR WMCON. RDY/$\overline{\text{BSY}}$ = 0 means programming is still in progress and RDY/$\overline{BSY}$ = 1 means EEPROM write cycle is completed and another write cycle can be initiated.

In addition, during EEPROM programming, an attempted read from the EEPROM will fetch the byte being written with the MSB complemented. Once the write cycle is completed, true data are valid at all bit locations.

Programmable Watchdog Timer

The programmable Watchdog Timer (WDT) operates from an independent internal oscillator. The prescaler bits, PS0, PS1 and PS2 in SFR WMCON are used to set the period of the Watchdog Timer from 16 ms to 2048 ms. The available timer periods are shown in the following table and the actual timer periods (at V_{CC} = 5V) are within ±30% of the nominal.

The WDT is disabled by Power-on Reset and during Power-down. It is enabled by setting the WDTEN bit in SFR WMCON (address = 96H). The WDT is reset by setting the WDTRST bit in WMCON. When the WDT times out without being reset or disabled, an internal RST pulse is generated to reset the CPU.

Table 7. Watchdog Timer Period Selection

WDT Prescaler Bits			
PS2	PS1	PS0	Period (nominal)
0	0	0	16 ms
0	0	1	32 ms
0	1	0	64 ms
0	1	1	128 ms
1	0	0	256 ms
1	0	1	512 ms
1	1	0	1024 ms
1	1	1	2048 ms

Timer 0 and 1

Timer 0 and Timer 1 in the AT89S8252 operate the same way as Timer 0 and Timer 1 in the AT89C51 and AT89C52. For further information on the timers' operation, refer to the Atmel web site (http://www.atmel.com). From the home page, select "Products", then "Microcontrollers, then "8051-Architecture". Click on "Documentation", then on "Other Documents". Open the document "AT89 Series Hardware Description".

Timer 2

Timer 2 is a 16-bit Timer/Counter that can operate as either a timer or an event counter. The type of operation is selected by bit C/$\overline{T2}$ in the SFR T2CON (shown in Table 2). Timer 2 has three operating modes: capture, auto-reload (up or down counting), and baud rate generator. The modes are selected by bits in T2CON, as shown in Table 8.

Timer 2 consists of two 8-bit registers, TH2 and TL2. In the Timer function, the TL2 register is incremented every machine cycle. Since a machine cycle consists of 12 oscillator periods, the count rate is 1/12 of the oscillator frequency.

In the Counter function, the register is incremented in response to a 1-to-0 transition at its corresponding external input pin, T2. In this function, the external input is sampled during S5P2 of every machine cycle. When the samples show a high in one cycle and a low in the next cycle, the count is incremented. The new count value appears in the register during S3P1 of the cycle following the one in which the transition was detected.

Since two machine cycles (24 oscillator periods) are required to recognize a 1-to-0 transition, the maximum count rate is 1/24 of the oscillator frequency. To ensure that a given level is sampled at least once before it changes, the level should be held for at least one full machine cycle.

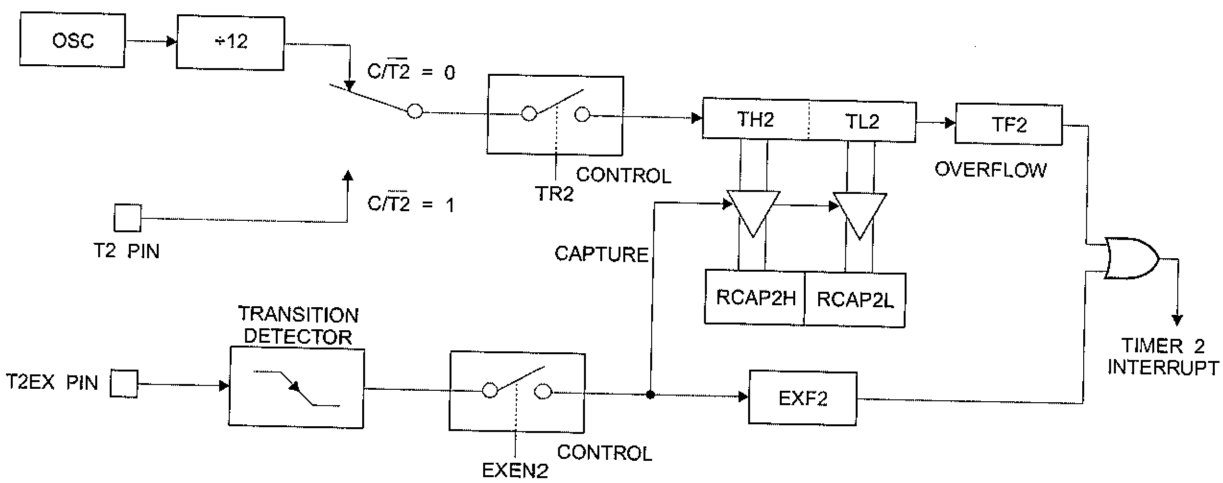
Table 8. Timer 2 Operating Modes

RCLK + TCLK	CP/$\overline{RL2}$	TR2	MODE
0	0	1	16-bit Auto-reload
0	1	1	16-bit Capture
1	X	1	Baud Rate Generator
X	X	0	(Off)

Capture Mode

In the capture mode, two options are selected by bit EXEN2 in T2CON. If EXEN2 = 0, Timer 2 is a 16-bit timer or counter which upon overflow sets bit TF2 in T2CON. This bit can then be used to generate an interrupt. If EXEN2 = 1, Timer 2 performs the same operation, but a l-to-0 transition at external input T2EX also causes the current value in TH2 and TL2 to be captured into RCAP2H and RCAP2L, respectively. In addition, the transition at T2EX causes bit EXF2 in T2CON to be set. The EXF2 bit, like TF2, can generate an interrupt. The capture mode is illustrated in Figure 1.

Figure 1. Timer 2 in Capture Mode



Auto-reload (Up or Down Counter)

Timer 2 can be programmed to count up or down when configured in its 16-bit auto-reload mode. This feature is invoked by the DCEN (Down Counter Enable) bit located in the SFR T2MOD (see Table 9). Upon reset, the DCEN bit is set to 0 so that timer 2 will default to count up. When DCEN is set, Timer 2 can count up or down, depending on the value of the T2EX pin.

Figure 2 shows Timer 2 automatically counting up when DCEN = 0. In this mode, two options are selected by bit EXEN2 in T2CON. If EXEN2 = 0, Timer 2 counts up to 0FFFFH and then sets the TF2 bit upon overflow. The overflow also causes the timer registers to be reloaded with the 16-bit value in RCAP2H and RCAP2L. The values in RCAP2H and RCAP2L are preset by software. If EXEN2 = 1, a 16-bit reload can be triggered either by an overflow or by a 1-to-0 transition at external input T2EX. This transition also sets the EXF2 bit. Both the TF2 and EXF2 bits can generate an interrupt if enabled.

Setting the DCEN bit enables Timer 2 to count up or down, as shown in Figure 3. In this mode, the T2EX pin controls the direction of the count. A logic 1 at T2EX makes Timer 2 count up. The timer will overflow at 0FFFFH and set the TF2 bit. This overflow also causes the 16-bit value in RCAP2H and RCAP2L to be reloaded into the timer registers, TH2 and TL2, respectively.

A logic 0 at T2EX makes Timer 2 count down. The timer underflows when TH2 and TL2 equal the values stored in RCAP2H and RCAP2L. The underflow sets the TF2 bit and causes 0FFFFH to be reloaded into the timer registers.

The EXF2 bit toggles whenever Timer 2 overflows or underflows and can be used as a 17th bit of resolution. In this operating mode, EXF2 does not flag an interrupt.

Figure 2. Timer 2 in Auto Reload Mode (DCEN = 0)

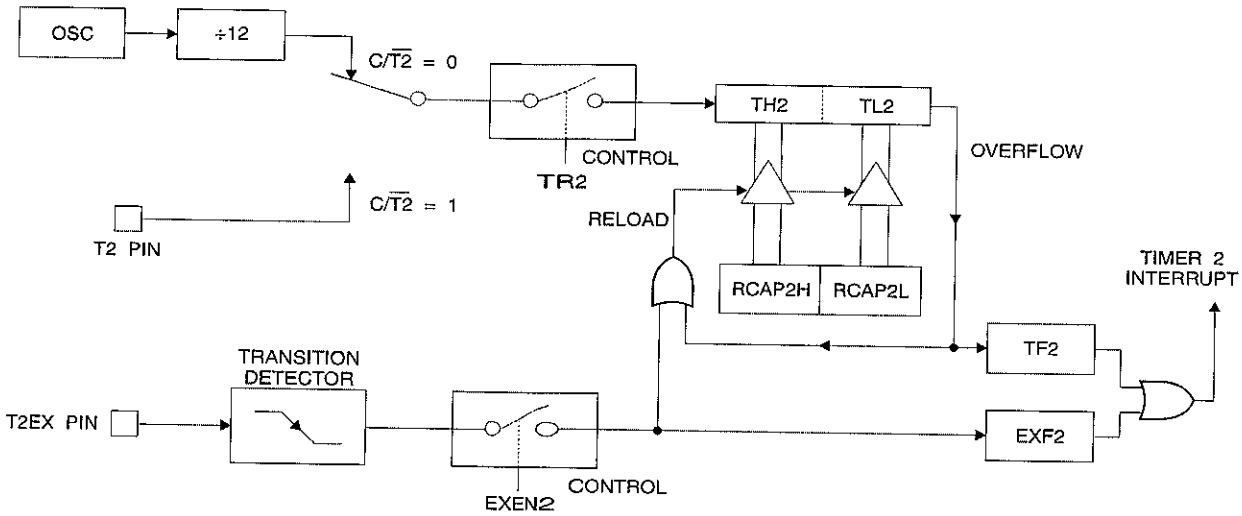


Table 9. T2MOD – Timer 2 Mode Control Register

T2MOD Address = 0C9H								Reset Value = XXXX XX00B
Not Bit Addressable								
	–	–	–	–	–	–	T2OE	DCEN
Bit	7	6	5	4	3	2	1	0

Symbol	Function
–	Not implemented, reserved for future use.
T2OE	Timer 2 Output Enable bit.
DCEN	When set, this bit allows Timer 2 to be configured as an up/down counter.

Figure 3. Timer 2 Auto Reload Mode (DCEN = 1)

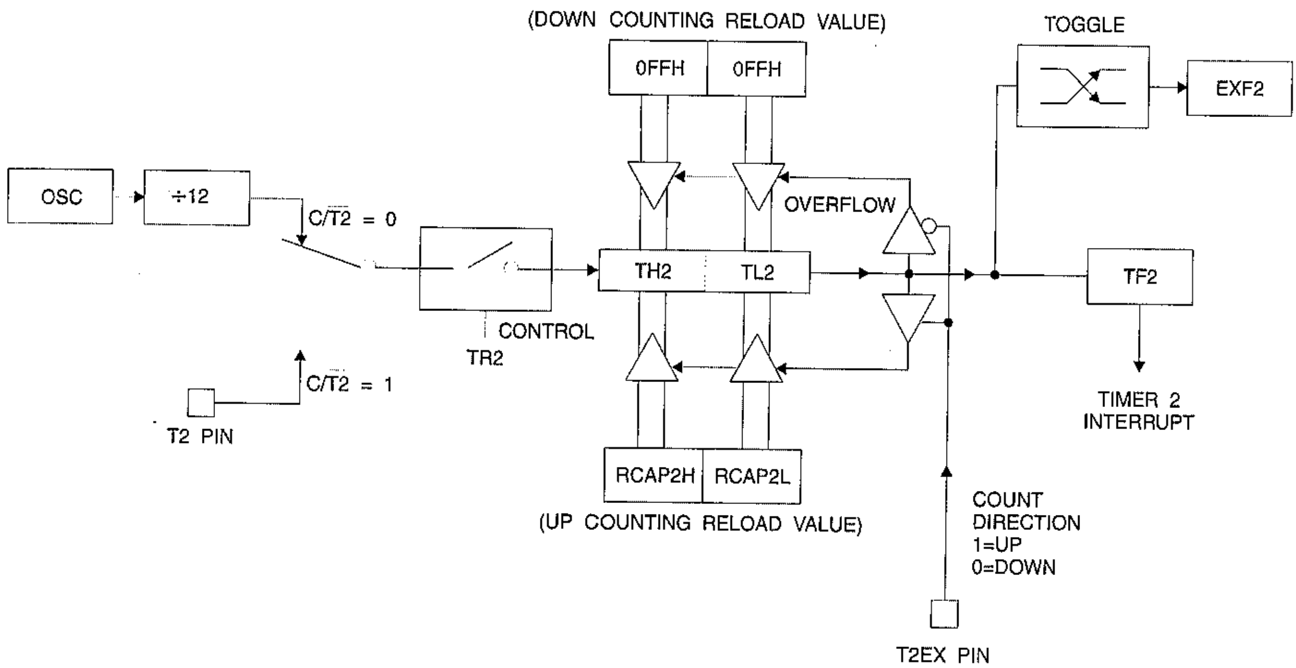
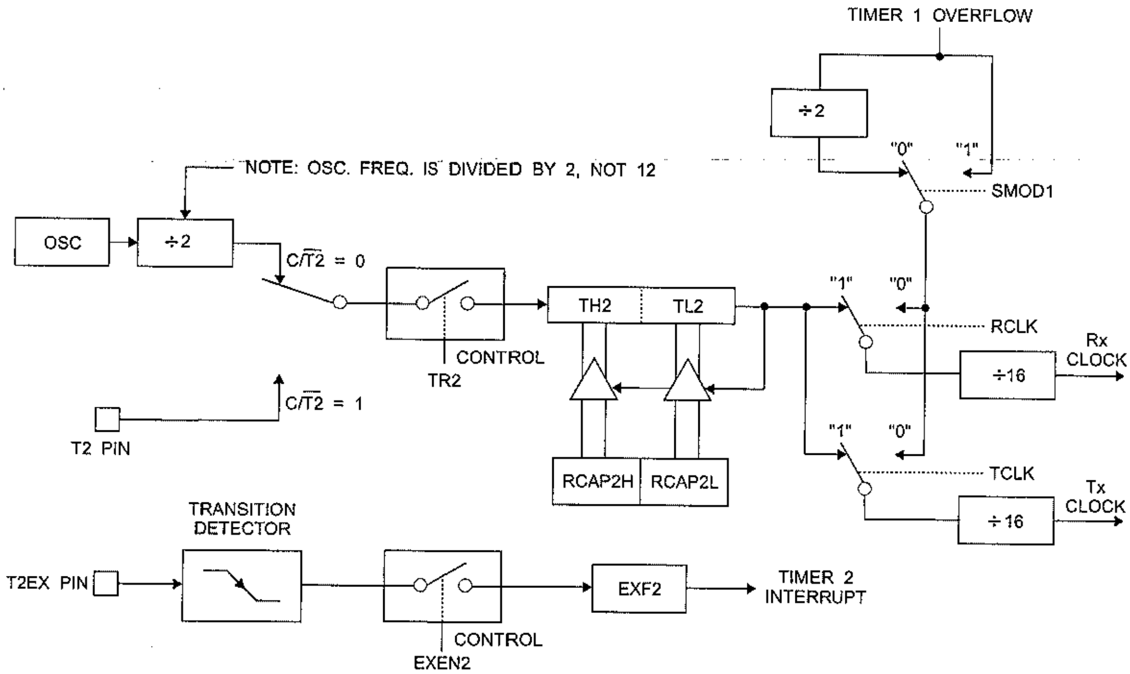


Figure 4. Timer 2 in Baud Rate Generator Mode



Baud Rate Generator

Timer 2 is selected as the baud rate generator by setting TCLK and/or RCLK in T2CON (Table 2). Note that the baud rates for transmit and receive can be different if Timer 2 is used for the receiver or transmitter and Timer 1 is used for the other function. Setting RCLK and/or TCLK puts Timer 2 into its baud rate generator mode, as shown in Figure 4.

The baud rate generator mode is similar to the auto-reload mode, in that a rollover in TH2 causes the Timer 2 registers to be reloaded with the 16-bit value in registers RCAP2H and RCAP2L, which are preset by software.

The baud rates in Modes 1 and 3 are determined by Timer 2's overflow rate according to the following equation.

$$\text{Modes 1 and 3 Baud Rates} = \frac{\text{Timer 2 Overflow Rate}}{16}$$

The Timer can be configured for either timer or counter operation. In most applications, it is configured for timer operation ($CP/\overline{T2} = 0$). The timer operation is different for Timer 2 when it is used as a baud rate generator. Normally, as a timer, it increments every machine cycle (at 1/12 the oscillator frequency). As a baud rate generator, however, it increments every state time (at 1/2 the oscillator frequency). The baud rate formula is given below.

$$\frac{\text{Modes 1 and 3}}{\text{Baud Rate}} = \frac{\text{Oscillator Frequency}}{32 \times [65536 - (\text{RCAP2H,RCAP2L})]}$$

where (RCAP2H, RCAP2L) is the content of RCAP2H and RCAP2L taken as a 16-bit unsigned integer.

Timer 2 as a baud rate generator is shown in Figure 4. This figure is valid only if RCLK or TCLK = 1 in T2CON. Note that a rollover in TH2 does not set TF2 and will not generate an interrupt. Note too, that if EXEN2 is set, a 1-to-0 transition in T2EX will set EXF2 but will not cause a reload from (RCAP2H, RCAP2L) to (TH2, TL2). Thus when Timer 2 is in use as a baud rate generator, T2EX can be used as an extra external interrupt.

Note that when Timer 2 is running (TR2 = 1) as a timer in the baud rate generator mode, TH2 or TL2 should not be read from or written to. Under these conditions, the Timer is incremented every state time, and the results of a read or write may not be accurate. The RCAP2 registers may be read but should not be written to, because a write might overlap a reload and cause write and/or reload errors. The timer should be turned off (clear TR2) before accessing the Timer 2 or RCAP2 registers.

Programmable Clock Out

A 50% duty cycle clock can be programmed to come out on P1.0, as shown in Figure 5. This pin, besides being a regular I/0 pin, has two alternate functions. It can be programmed to input the external clock for Timer/Counter 2 or to output a 50% duty cycle clock ranging from 61 Hz to 4 MHz (for a 16-MHz operating frequency).

To configure the Timer/Counter 2 as a clock generator, bit C/$\overline{T2}$ (T2CON.1) must be cleared and bit T2OE (T2MOD.1) must be set. Bit TR2 (T2CON.2) starts and stops the timer.

The clock-out frequency depends on the oscillator frequency and the reload value of Timer 2 capture registers (RCAP2H, RCAP2L), as shown in the following equation.

$$\text{Clock Out Frequency} = \frac{\text{Oscillator Frequency}}{4 \times [65536 - (\text{RCAP2H,RCAP2L})]}$$

In the clock-out mode, Timer 2 rollovers will not generate an interrupt. This behavior is similar to when Timer 2 is used as a baud-rate generator. It is possible to use Timer 2 as a baud-rate generator and a clock generator simultaneously. Note, however, that the baud-rate and clock-out frequencies cannot be determined independently from one another since they both use RCAP2H and RCAP2L.