This paper is concerned with a program that's being sponsored by the Air Force for the purpose of building an adhesive bonded structure. A discussion will be given on some of the problems that we are currently trying to address; what we are doing to solve these problems; and some of the road map programs that will support the Primary Adhesive Bonded Structure Technology (PABST) program. This program is under contract with the McDonnell-Douglas Corp., Long Beach.

The objective of this program is to demonstrate and validate that by the use of adhesive bonding as the primary joining method that a structure can be fabricated that will be cheaper, lighter in weight, and reliable. The approach is to review and analyze several design configurations and select a single design for fabrication. To support this decision testing will be accomplished on actual test components representative of the design selected, in addition to extensive coupon testing. After fabrication the structure will be subjected to several life cycle tests at the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.

The test component will have the type of configurations as shown in Fig. 1. The baseline aircraft for this test component will be the Advanced Medium STOL Transport (AMST) airplane. The test component will be 50 feet in length and 18 feet in diameter.

The total program will cover a span of 4 1/2 years. During the first phase of the program there will be a selection of three designs; the selections will be made sometime about September of this year, and a selection of one design for fabrication will be around January of 1976. The next two phases will include a detail design phase and a fabrication phase with the fabrication phase covering a 15 month period. After fabrication the article will be tested in four lives: fatigue, damage tolerance, static augment and a teardown inspection.

During the course of this program we will fabricate specimens representative of the structure. These specimens will be used to develop nondestructive testing (NDT) techniques. Some of the problems that we will be involved with are: multiple bond line inspection; inspections where we have adhesives and form adhesives; and also the inspection of complex geometry. The metal-to-metal type and the honeycomb type present similar problems for use in NDT evaluation.

In general the resolutions and sensitivity of NDE techniques needed to assure a reliable structure are not available in the current state-of-the-art. This is due primarily to a limitation of equipment, for instance, in the case of ultrasonics we do not have reproducible transducers. Our reference standards are not adequate. We cannot simulate actual defective conditions within a structure. Many times in the building of reference standards we use a teflon
Fig. 1. Primary adhesively bonded structure test component used in this program.
insert and other types of artificial defects that are lost during the bonding process. There is a lack of problem definition. The question is what is important for nondestructive testing to measure? The failure mechanisms of a bonded structure have not been adequately defined. Is it the cohesive strength of the material that is important or is it adhesive failure that we will want to measure? What is an adhesive failure? Is that the failure between the adherent and the adhesive? Or is it the failure between the anodization or the primer that protects the adherent? These modes of failure have not been adequately defined.

There is very little data on the effect of defects, even those defects that we can currently detect with nondestructive testing. Large porosity, gross voids, and gross delaminations are easily detected, but there is not sufficient data to relate these types of defects to their effect on the strength of the bond.

Let us go to the process of starting to put a bonded joint together. The metal alloys in general are pretty uniform; we don't have too much problem there in inspection. But when we come to the adhesives, they are variable from batch to batch, and they're not dependable for use to the extent that you can take them off the shelf and put them into a bonded structure. We do not have NDE techniques that are economical and adequate to inspect adhesives, incoming adhesives.

Looking at the adhesive bonding process itself, surface preparation is of utmost importance. Is the surface properly anodized? We do not have techniques that can tell us whether or not we do have the proper thickness of anodizing on the surface. Surface contamination, as a result of greases, chemical changes within the environment and environmental dust, is a major problem for control. We do not have techniques that can adequately determine whether or not the surface has been contaminated prior to bonding.

The fitup of detailed parts is another important problem. Many manufacturers use verifilm to assure proper fitup of detailed parts, but this is quite expensive. There is a need to develop NDE as we do not have techniques that will give us the capability to say whether or not we have good fitup of parts.

During the cure cycle, many adhesives, due to their chemical composition, cure at different rates. There are some techniques that give some indication of when an adhesive is properly cured, however, we do not have the capability to measure that point wherein we can say that an adhesive is properly cured. This is important to measure for the prevention of under cure and over cure conditions.

The next step in the manufacturing process is putting the component together. Once the component has been put together, shape becomes a problem. Many techniques, because of the complexity of the shape of the bonding component, are not capable of adequate inspection. In general, if they are
large voids, large delaminations, we can use ultrasonics, radiography and
the tap test to find these types of defects.

Techniques commonly used for adhesive bond evaluation tests are limited,
in particular, in locating flaws in complex shaped structures, especially
where you have doublers and far side disbons or where there are bonds at
the second interface.

Once the component becomes assembled into a larger part, then, there is
a question of whether or not you have damage as a result of assembly, that is,
free edge damage. We do not, except for visual examination, know whether
or not this type of condition occurred. There is a definite need to have some
type of NDE technique to determine the quality of the interface. There are
no reference standards for inspection of the assembled component.

Accessibility to inspect is another major problem, the ability to get
into areas for proper inspection. Inspection during service finds that NDE
techniques that are useful during the production cycle are not adequate for
inspection during the time that the part is in service.

One of the bigger demands on the NDT engineer is to provide methods to
determine the strength of bonds. Current techniques using the Fokker bond
tester can, in some cases, indicate the cohesive strength of a bond; however,
for production use this instrument is limited due to thickness of aluminum
skins. An NDE strength relationship is needed to predict the life of bonded
structures.

Contamination in the form of corrosion is one of the conditions which
must be detected while the bonded structure is in use. The ability to detect
this condition will give some indication of the strength of the bond. Where
areas are repaired, we do not have adequate techniques to tell us whether or
not we have made a good bond as a result of the repair.

In the PABST program we will attempt to use the current-state-of-the-art
NDE techniques and do some modification where necessary to accomplish the
NDE evaluation for production and service inspection. During the program
specimens will be fabricated with intentional defects, and additional panels
will be selected for test with natural defects that occur during the manu-
factoring cycle. Then, from these NDE evaluations, we will determine the
optimum methods to use during the program. The methods that we plan to
investigate and radiography, ultrasonics, the Fokker bond tester, and
Shurtronics bond tester technique. We will also look at techniques that can
provide us a capability to inspect panels that are quite large. Panels that
we’re talking about in this program will be about 30 feet in length and 10 feet
in width. So, we definitely need a large area of scan capability.

One of the significant things that we will be doing in this program is
to have the NDI engineer, along with the Quality Control people, review each
and every drawing. The purpose is to make sure that the final design will be
an inspectable design. During the selection of three designs, a system will
be developed to rate these designs as to their inspectability. This system
will be based on: the sensitivity of the NDE technique; the ease in the use
of the technique and the accessibility to inspect. This rating system will reflect on the ability to inspect during production of the item and the maintenance of the item at a depot or in the field.

During the course of the program we will develop acceptance criteria. This will be accomplished by the production of defective specimens to be used during the production and also during the service. We will develop defect standards, and we will provide instrument calibration. We will look at the Fokker bond test technique in order to try to get some indications of correlations that we can make so far as strength of bonded specimens in this program. We will develop procedures and specifications for production parts, for process control and bond assembly inspection itself. NDE procedures will be developed for the ADP component, and for inspection during full-scale test, and for repairs.

There are several programs that will support the PABST program that are called the road map activities. I will not go into detail on all of these programs, but I will discuss one or two which we think will give us some immediate payoff for nondestructive inspection of bonded structures. We have direct coordination with the development activities on these programs. This is accomplished by contractor meetings and by actual onsite review of the things that we're doing on the PABST program.

The first program I will discuss is to determine those flaws that most commonly occur in large area metal-to-metal and metal-to-honeycomb adhesive bonded structures. We will try to evaluate the ability of the state-of-the-art techniques to detect and discriminate between the critical and the non-critical defects. The approach will be to fabricate large test panels with natural flaws that occur during production and use current techniques to locate and determine the flaw size and type. To determine the severity of these flaws tests will be conducted under high and low cycle fatigue and aggressive environments and NDE will be used to monitor flaw growth.

Flaws will be introduced into the bond line in several of these types of specimens, and they will be destructively tested for the purpose of correlation to the NDE indications. At the end of this program, it is expected that written NDE procedures for the detection of bond line flaws and for fabricating standard flaw samples for use in production inspection will be provided. One of the important things that we hope to do in this program is to evaluate the cost of each inspection procedure.

Another program will address the problem of surface preparation through the characterization of surfaces prior to the adhesive bonding process. This program's purpose is to demonstrate that the scanning electron microscope (SEM) can be used to measure the anodized surface oxide composition thickness and morphology. This is really an important parameter, the thickness of the oxide and its composition. This program is being conducted by the Northrop Company under contract with the Air Force (AFML). The approach will be to use the scanning electron microscope to measure the surface quality as to its composition and thickness. It will also be used to monitor the anodizing process in both the composition and the temperature. There will be coupons put into the PABST program to run along with the production anodizers and the resulting information fed into the PABST program for the purpose of developing
a technique that can be used on the production floor. Standards will be developed and limits defined for the aluminum anodized surface quality, and the effort will determine the SEM reliability.

A second program somewhat similar to the above program is one where the only difference is that an actual portable instrument will be provided. Many of the things that will occur in the previously discussed program will occur in this program in order to develop an instrument and determine its capability and application for production use during the course of the PABST program.

Another program is designed to develop a technique that can define the exact point during the cure cycle of adhesives for an optimum process. One of the suggested techniques is to use the electronic spin resonance (ESR) method as a technique to determine the optimum temperature cycle and cure cycle for adhesives. Work has not started on this program. It is planned for a start in fiscal 1977.

Another problem is to determine the location of the defect and what is the size of the defect in a particular layer in the adhesive system. This program's objective is to develop a nondestructive technique with improved sensitivity and capability to discriminate defects in multilayered bonded systems. The current capability can, in many cases, detect a defect in a multilayered system but it cannot tell you exactly where that defect is nor its size. The approach here would be to investigate current nondestructive techniques, such as ultrasonics, and determine their capability to detect defects in splice plates, honeycomb closeout members and multilayer panels.

The major deficiencies in nondestructive testing are: the inability to measure the strength of the bonded structures; the inability to inspect in between the laminates of the bonded structure; and the inability to inspect the item after it's been put out in the field. The most commonly used type of inspection found in the field was the tap test. This is not a reliable test because of the dependence on personnel interpretation which is often subjective. In some cases we found that radiography was used along with some ultrasonics; however, these techniques were used in specialized cases. The strength measurements are becoming a great problem as far as the detection of corrosion is concerned. Can we detect corrosion to determine its effect on the bond line? We do not have techniques for this.
DISCUSSION

DR. LES LACKMAN: We have a little time for questions. Yes, sir?

DR. JOHN GOODMAN (Aeronautical Systems Division): Two questions. One, on the specimens you're going to make with built-in defects, are those going to include coupons as has been referred to as well as specimens with areas of no bonds and foreign objects?

MR. SHELTON: The program will not address the problem of weak bonds. It will only address problems wherein there will be bonds with voids and delaminations.

DR. GOODMAN: Okay, that leads to my next question, which is: do we even know how to conduct a destructive examination, a teardown inspection and say what the defects were? Can we do that without destroying the defects?

MR. SHELTON: Can we do that without destroying the defects?

DR. GOODMAN: Yes.

MR. SHELTON: In many cases you can't. I think that's the reason, I mean that's the sort of gray area between preparing a proper test to determine whether or not your nondestructive testing is effective. You have to go to the point wherein you have to actually put a known defect within the bond in order to know that you have detected it. Once you destroy it you know you have put it there. So, that's about the only approach to that. Did I answer your question?

DR. GOODMAN: I'm afraid you did.

MR. GEORGE EPSTEIN (Aerospace Corporation): Bill, first let me thank you for a very fine presentation, very thorough.

MR. SHELTON: Thank you.

MR. EPSTEIN: I noticed that you did not mention holography in any of your activities. Could you comment on that?

MR. SHELTON: I didn't mention any particular technique, per se, except the techniques that we are using. We do plan to get some work in holography started in the area of large scan capability. Really, we have a small program going within the laboratory. We're looking at holography as a means to use in production inspection and/or field inspection.

MR. BILL HODGETTS (Rockwell International): I'd like to know if before you tear those pieces apart somewhere in the process are you going to try the nondestructive technique that you think will find those flaws and put on record what you see when you do these?

MR. SHELTON: This is being done now. In the PABST program every engineering specimen is onestuctively tested by some method. Maps are made, records
are kept, and once these specimens are destructively evaluated each
surface is looked at to determine whether we have a cohesive failure or
adhesive failure relative to their material property as far as strength
is concerned, and a correlation is made between nondestructive testing
and destructive tests.

MR. LEE CROCKETT (Rockwell International, Space Division): I would like to
know when you talk about ultrasonics are you talking about pulse echo
or through transmission?

MR. SHELTON: Well, we're talking about pulse echo, through transmission, the
reflector technique, the whole works.

MR. CROCKETT: For your honeycomb structure, too?

MR. SHELTON: Yes.

MR. CROCKETT: Okay. Interesting.

PROF. BRUCE MAXFIELD (Cornell University): Is any use being made of optical
fluorescence methods to either characterize surfaces or the materials that
are being used?

MR. SHELTON: No.

PROF. MAXFIELD: Because it seems to me the fluorescent spectrum of materials
is often influenced rather substantially by small levels of contaminants
that are introduced. This could be true of either the surface or, in
materials such as epoxy, of any variability in the material.

MR. DICK REYNOLDS (ARPA): I was a little bit surprised in this emphasis on the
Fokker bond tester because that's a piece of equipment which has been
available for about 20 years and has been entirely investigated at 5 year
intervals ever since. So, you can't really expect anything very new
to come out of this. The value and the limitations are, in fact, very
well established. What I would like to say, very briefly, is that I
think we have evidence that in the analogous problem of delamination in
fiber reinforced composite material, there are two possible ways ahead,
which seem to have been overlooked.

One can extend the idea of the Fokker bond tester by introducing larger
testing strain, larger testing shear strain. Now, of course, many
structures won't tolerate this, and, therefore, the technique is not
applicable. The other possible approach is where the crack is surface
opening. In this case, of course, fluorescent dye penetrating techniques
are available, but if you want to find how far the crack extends into the
structure, then one wants to have some sort of radiographic opaque
penetrant, such as, for example, carbon tetrachloride, which although a
very undesirable material to have around the place, nevertheless can be
very effective in showing up the extent of the cracks in fiber reinforced
structures.

Now, I think the point about this is that, looking again at ultrasonics,
low strain methods, looking again at things which have been tried before,
they're not likely to tell us anything new. What we have to do is to look for things which might conceivably tell us something new. If they are not applicable to particular structures, then that is the time to give up.

COL. RON NOKES (Kelly Air Force Base): Bill, toward the end of your briefing you mentioned a program to develop new NDE techniques not associated with the PABST program. Is that an ongoing program with someone now, or is that something that's being planned for the future?

MR. SHELTON: Some of the programs that were discussed previously are ongoing programs, these are ongoing programs. I can give you a list of these programs if you'd like?

COL. NOKES: Well, I'm concerned about one specifically, whether there is any effort toward new--

MR. SHELTON: Which one was that?

COL. NOKES: I don't recall now.

MR. SHELTON: Was it the adhesive curing monitor system or multilayer--

COL. NOKES: No, you had a chart that said that there's a program for development of new NDE techniques for bonded structures.

MR. SHELTON: I'll have to give it to you a little later.

COL. NOKES: Okay.

MR. GEORGE DARCY (Army Research Center): Is any special effort being taken to insure the separate and identifiable reporting of the NDT, NDI, NDE effort here in this contract so that the results don't get mixed in with other aspects of the overall project or not reported at all? I think there has been a history of much excellent NDE work that has been done in the past that is being buried or not recorded at all, and this seems like a very ambitious and very excellent program, and I think that a special effort should be made to exhibit the NDE results from it.

MR. SHELTON: Very good comment. We are making a special effort to have a separate section in our semi-annual reports regarding the NDE activities. The techniques are fully described, their results and their correlations.

MR. GEORGE EPSTEIN (Aerospace Corporation): Won't there also be some interchanges within the industry and opportunities for discussion relative to that program?

MR. SHELTON: Yes. There will be several design reviews during the course of this program. The first one I think is September, isn't it, Nate?
MR. NATE TUPPER (WPAFB): No. It will be probably after completion of Phase I, Bill, the Phase I preliminary design review. That will be sometime next summer probably.

PROF. JOE ROSE (Drexel University): I just wanted to make a comment in technical philosophy. The comment was made earlier by the fellow from Harwell about the bond tester at Sony. If someone says, "We tried that method or technique five or ten years ago and it didn't work then, therefore we should rule out the consideration of it today:" this is certainly in error. There are so many new things happening, new understanding of principles, techniques, methods, better test specimens, better organized programs, etc. I just want to make a comment that I'm sure we're all aware of again, because something didn't work five years ago doesn't mean it won't work today; there's a good chance that it might.

MR. ALEX BERRY (NASA-Lewis Research Center): You mentioned that you're going to rate structures relative to inspectability. I wonder what impact this will have on the philosophy of the Mil-Spec 1530 relative to making things more inspectable, assuming that noninspectability is not always inevitable.

MR. SHELTON: I hope it has quite a bit of influence on that particular spec. I know in this program that we are driving to influence the selection of designs so far as the designers are concerned; if we can't inspect an item we don't want that design. So, hopefully, this will translate into that particular spec.

MR. DAVE KAELBLE (Rockwell International Science Center): I was particularly interested in your comment on the electron spin resonance method for curing. Is this meant to be developed as an acceptance test for incoming material?

MR. SHELTON: It is being proposed, yes. One of the techniques that they will be looking at.

DR. LACKMAN: Any more questions?

MR. CAL KAMMER (Rockwell International Space Division): One thing that's very profound using NDT methods to detect defects is the size consideration. And one thing that happens so many times is that you feel that you have built a defect of a certain size, but by the time you go to inspect the part it is no longer that same size, yet your data will show that x instrument did or did not detect y dimension defect, and this is very misleading. Many things that arise today, as far as designer picking a size for a defect that he will design is concerned, are based on data that are very incomplete. Now, I guess what I really would like to say here is, are you going to address this size consideration on making defects to make sure that you do control the sizes accurately?

MR. SHELTON: This will be the objective of the program to get the one to one correlation between the actual defect size and the NDE measurement. As you say, it's quite difficult to do, but, hopefully, that program will address that particular problem. I'm not the monitor on that
particular program, and we are looking to that program to feed into
the PABST program. But I'm quite sure that they will take this into
consideration.

MR. STUHRKE (Martin-Marietta): We have some interesting things to go along
with this. We've done some recent work in adhesive bonding as a
result of a problem we had in the field, and we had three
distinct populations. We had a large structure, which failed under
a set of conditions. We used the optimum cure cycle, the optimum
everything, optimum cleaning cycle and all that to give you the best
properties for a test specimen which is supposedly similar to it
except for size. In other words, we've seen very distinct size
effects, geometric effects, using the same alloy, the same cleaning
cycle, the same adhesive, the same bonding cycle. We don't really
know enough about the basics of adhesives bonding, and our real problem
appears to be in the interface. I can't tell, for example, why given
one set of conditions I get a slickoff failure and another set I get
an adherence failure. I get the same properties in a tensile test, and
yet I get an entirely different fracture surface, both in a small specimen
or a drum peel specimen or a big specimen.

Now, in the program that you laid out, is there going to be much
emphasis on the basic nature of adhesive bonding and particularly
the interface?

MR. SHELTON: I think one of the things that will sort of help to solve
that particular problem is that we are defining the surface prior
to bonding, an optimum surface prior to bonding. We will come up
with an optimum anodizing surface, an optimum primer and a selective
technique for the adhesive. I don't think this has been done before.
Some of the failures that you're talking about occurring is one
condition and not in another condition I think will be controlled by
this approach.

MR. STUHRKE: Well, just to go along and follow that up a little bit, we
had some experience where we have shown a difference where under similar
conditions of anodizing, the only difference we could tell was a minor
difference in the alloy content. In other words, we had some 2219
aluminum, and it was anodized under the same set of conditions and
the same batch, and one set of specimens failed in a much lower popu­
lation than the other, and in going back through the entire cycle, the
most obvious thing was there was a slight difference in the two alloys
and the populations. Now, I saw some data the other day on how you
look at populations, and it gives me sort of a queasy feeling, but
there are so many different variables in the adhesive bonding business
that we have to get a handle on.

MR. SHELTON: Right.

MR. STURKE: I know the next paper is going to consider the moisture problem.
We've got years of data which show that, at least in Orlando, we can
plot, let's say, the goodness of our adhesive bonding processes as a
function of the time of the year. We make excellent bonds in
the winter when the humidity is, for Orlando, is down around 40 percent.
In the summer, when the humidity is 100 percent, we make lousy bonds.
So, if you want to buy some stuff from us, make sure we make it in the
winter.

DR. LACKMAN: We will remember that. Now, how about time for one more
question? George?

DR. GEORGE ALERS (Rockwell International Science Center): You've described
a program for bonding aluminum parts. Is there a similar program for
fiber reinforced composites that is coming up in the future?

MR. SHELTON: No.