Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

memorandum

TO: Cary Skidmore, M-4, MS P942

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FROM: Niels R. Borch, J-6 NRB

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SUBJECT: DISCUSSION OF M-4 CONFINEMENT VESSEL HISTORY AND RECOMMENDATION FOR MATERIALS FOR DAHRT VESSELS

DISCUSSION OF CONFINEMENT VESSEL HISTORY

The confinement vessels and safety vessel that are used to contain products of explosive experiments using the current configuration of PHERMEX were designed in the early 1970's. The containment vessels were designed such that they would without question survive explosive loading to their elastic limit, in the presence of major flaws. The methodology, in simplified terms, was to transfer all of the radial momentum of the products of the explosion to radial momentum of the vessel shell and to trap this energy as elastic stored energy in the vessel shell. This methodology was developed for the vacuum case, which is the usual situation at M-4 because it eliminates the sharp shock which would arrive at the confinement vessel wall if a gas were present in the vessel. These vessels are expected reach local yield during such experiments and in fact they do, with observable deformation. The gas pressure imposed by the explosion is actually surprisingly low. It is on the order of one order of magnitude lower than that required to cause any yielding in the containment vessels.

The safety vessel has somewhat different requirements. It has to contain the products of the explosive experiment if the confinement vessel should fail. If the failure is by a leak the pressure would be very modest and the products should be easily contained. If the confinement vessel were to fail catastrophically, and separate into several fast moving pieces, a very improbable event, the safety vessel is supposed to stop them without allowing any leakage.

I will only address confinement vessels in the rest of this discussion.

A very thorough quality assurance (QA) plan was developed for this project. The critical test used in the QA plan was the dynamic-tear test (DTT) using 5/8" thick specimens which was developed by the Naval Research Laboratory shortly before the vessels were designed. This test measures the energy required to propagate a crack as a function of temperature. The results correlate very well with real world failures and fracture performance can be predicted for very thick materials. This was a very conservative approach which utilized the state-of-the-art at the time. The performance criterion that the DT test guarantees is the ability of the vessel materials to arrest cracks on the order of three times the wall thickness in length at stresses at or slightly above the yield stress, under impulse conditions. It also defines the minimum service temperature, i.e., the temperature above which this performance is assured.

The quality assurance program for the last lot of confinement vessels obtained got off track, I believe mostly for budgetary reasons, in that the dynamic-tear testing was not done in a timely manner after the vessels were received by M-4. MST-6 (then CMB-6) was tasked to perform the mechanical testing for the minimum service temperature certification of the 6 foot diameter by nominally two inch wall thickness vessels, which were obtained by M-4 in 1978. The test specimens were sent a few at a time and eventually the testing was done except for the specimens from the vessel shells because the material had apparently been lost. I located the missing material and the testing was completed in 1986. The shell material turned out to be the limiting material insofar as minimum service temperature was concerned in all but 2 vessels, and 11 out of 16 vessels tested could not be used below 90 degrees F. Two of them required use above 136 degrees F to assure no failure.

This was a very unpleasant surprise, to say the least. The material, ASTM A537 Class 2, was selected for its perceived high ductility and reported excellent fracture resistance at fairly low temperatures. I have copies of two of the mill certifications for the 2 inch thick plate that the hemispherical heads were produced from and the reported nil-ductility temperatures (NDT) were -60 degrees F and -20 degrees F. At the time this material was obtained it was generally believed that the desired level of fracture performance would be achieved at NDT plus 60 degrees F, so vessels made from these plates were expected to have been safe at 0 or 40 degrees F. Vessels with thinner walls made from the same type of material had been previously purchased and the shell material apparently was not the temperature limiting factor. The fracture properties of the plate may have been degraded by the fabrication into heads or by the post-weld normalization heat-treatment.

I offer two criticisms of the previous design for your consideration. The first is that the design treated the vessels as pressure vessels with the pressure high enough to yield the material, at high loading rates. I believe they were therefore designed per the pressure vessel code which requires normalization after welding. The usual reason for normalization of welded structures is primarily to reduce residual stresses to very low values so that they can not be operative in initiating fatigue failure. We have only one load cycle so there is no fatigue possibility.

There may have been a misperception that the residual stresses from welding could cause premature localized yielding leading to failure. I believe that, while early yielding might occur during a confined experiment due to localized welding induced residual stresses superposed on applied stresses, it could not really lead to a vessel failure on one very short loading cycle. The actual static pressure that these vessels have to contain is only a couple of hundred psi. The peak stresses in the vessels are a result of impulse loading as the radial momentum of the products of the explosive experiment is transferred to the vessel wall. We know that there are many areas in the vessels that yield due to this load or to stresses experienced during ring down. The dynamic tear-test based design criterion used for these vessels requires a through thickness crack roughly three times the wall thickness to be present at the yield stress for catastrophic fracture to initiate. Such cracks would almost certainly be arrested, at least momentarily, with these vessels. We also now know that a crack running in possibly less fracture tough areas (such as a weld heat affected zone) in such vessels turns in response to the principal tensile stress component of the changing stress field as the vessel rings down, and that as soon as it turns into tougher material it arrests. This in fact has been observed in a non critical overtest.

I therefore want to raise the issue of there possibly being no real need for the post-weld normalization heat-treatment. These confinement vessels are not normal pressure vessels. They will experience only a couple of significant experimental loads. The vessel responds to these loads and then rings down in a very complicated manner, yielding where constructive elastic waves interferences of sufficient magnitude occur. I believe that residual welding stresses will play no important role in this phenomenology. The small amount of plastic behavior observed after such tests mean that even the superposed stresses can never rise very far above the yield stress.

The second issue I would like to see discussed is the requirement for hydrostatic testing of these vessels. I believe that this requirement exists only because of pressure vessel code requirements. It is considered necessary for normal pressure vessels to assure that the vessel will operate as intended, and that there are no defective materials or undetected critical flaws in them. All we really learned from these tests is that local non-elastic behavior occurs around nozzles at lower than expected pressures, and that in fact there are no through-thickness leaks. We invest considerable effort and expense in quality assurance to guarantee that no large flaws exist in the vessels, and it is my belief that this should be sufficient to assure fracture safety with the quality of materials we use. Why pressurize M-4 confinement vessels until they yield somewhere when the maximum actual experimental pressures ever imposed may be an order of magnitude lower? Also, these vessels do not have uniformly thick walls. The equator is about 50% thicker than the poles due to fabrication methods. As a consequence the hydro test does not guarantee the impossibility of crack propagation at the yield stress everywhere in the shell anyway.

MATERIALS

There are two material choices that I will discuss. The first is to change a minimal amount from previous experience and to make new vessels with the very best ASTM A537, Class 2, plate that can be obtained. Unfortunately such plate currently is produced only outside of the USA. EG&G in North Las Vegas utilizes foreign produced A537 material in their fabrication of downhole "racks" for LLNL nuclear experiments. Figure 1 shows the DTT data for a Japanese made steel compared to a typical US produced steel as used by M-4 for the shell of 2 inch thick confinement vessels. For the sake of comparison look at the temperature at which 800 ft.lb. 5/8" DTE is reached. Add 40 degrees F for the thickness correction and you see the problem. There is a 120 degree F performance penalty for using what was considered to be very good domestic steel over what was normal production material from Japan. The steel industry in the United States still lags behind the rest of the western world in application of the state-of-the-art technology to structural steelmaking practices, especially for materials to be used in low temperature service. Also on Figure 1 is data for EG&G as-welded material. If we could achieve similar properties in spherical vessels in the as-welded condition or welded and normalized condition I have no doubt that we would never have to concern ourselves as to ambient conditions for confined testing at LANL. If this recommendation is implemented extreme care has to be taken to assure that material of adequate quality is obtained, and that the low temperature fracture resistance performance is not degraded by subsequent fabrication into vessels. It might even be prudent to have the spherical heads or the vessels themselves produced to guaranteed DTT properties. This would be difficult as it is not normal commercial practice.

The second choice is to fabricate the new vessels from the new copper precipitation-hardened high strength, low alloy steels, the generic HSLA steels, which have been developed primarily by and for the US Navy. These steels have been developed for surface combatant ship service and will eventually be utilized for submarine pressure hulls. These steels are improved versions of ASTM A710, which we in fact utilized under a different specification for forged collars on previous vessels. They can be obtained from domestic manufacturers per MIL Specs with guaranteed DTT properties. They are certified for Navy use on the basis of explosive bulge testing at -40 degrees F, a far more severe test that we have ever used. These tests are performed on plates containing through thickness welds with sharp crack starters present. The HSLA steels are used by the navy in the as-welded condition. There is an insignificant heat affected zone effect as these steels contain very little carbon.

These HSLA steels are available in both 80 and 100 ksi minimum yield strength grades. The Navy qualified welding procedures are demonstrably adequate for our application, in the as-welded condition. There is recent data indicating that post-weld normalization may degrade the fracture performance insignificantly. The increased yield strength with assured fracture performance that these materials offer has to increase safety and certainly provides some experimental growth capability in that HE limits could be raised.

This choice is perhaps somewhat riskier because no one, as far as I have been able to determine, has ever produced a pressure vessel from these new steels. There is nothing inherently difficult in producing such a shape with them, it simply has never been attempted. We would have to bear some added developmental costs and some risk in fabrication with a new material.

RECOMMENDATION

I believe that it is part of LANL's responsibility to advance technology in the commercial sector where is is possible to do so without significant risk to its programs. This is such a situation. At this time I believe that the application of the new HSLA steels to the confinement vessel technology is possible, timely and prudent. This is my recommendation.

We know that there are problems with the past fabrication efforts with A537 steel and probably would have to invest as much in development activities with this steel as with the HSLA steels to assure that we achieve the intended fracture performance capability.

I further recommend that the use of the US Navy explosion bulge test on confinement vessel porthole cutouts be implemented as the proof test for any new vessels. It certainly is more representative of what we are really doing, and can be an overtest if desired. DT testing should still be used as the principal quality assurance tool, as before.

I believe that we can obtain vessels for 0 degree F service if the above recommendations are implemented.

NRB:pl

Distribution:
Tim Neal, M-DO, MS P915
Jay Boettner, M-4, MS P940
N.R. Borch, J-6
J-6 File

A537 DTT DATA
2" PLATE